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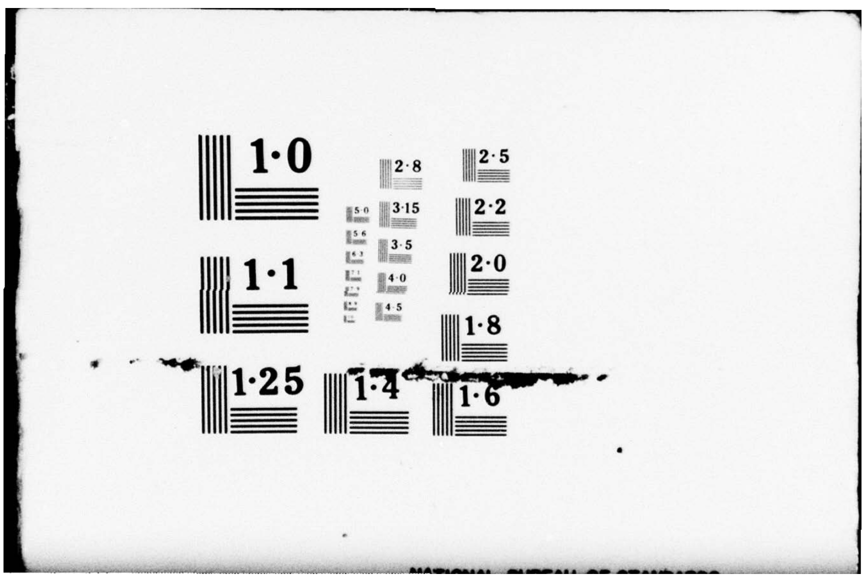
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THE UK ION THRUSTER SYSTEM AND A PROPOSED FUTURE PROGRAMME.

by

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THE UK ION THRUSTER SYSTEM AND A PROPOSED FUTURE PROGRAMME

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SUMMARY

The technology of the UK's ion thruster system and its development status in May 1976 are described and a detailed programme is proposed for developing the complete system for operational use in 1983.

Departmental Reference: Space 525

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PREFACE

For many years, a number of electric thruster systems[1,2] have been under development in Europe for both the primary and secondary propulsion applications on a variety of spacecraft. More recently, the north-south station-keeping (nssk) mission has seemed the most likely initial application of this new technology, and the various European development agencies have tended to concentrate their efforts on thrusters destined for this role. Progress has been sufficient in three countries, France, Germany and the UK, for their respective thruster systems to have reached the stage, at the time of writing, where a decision regarding further development to flight status is very desirable.

In March 1975 the French delegation to ESRO formally suggested[3] that further simultaneous development of all European nssk thrusters would represent a considerable waste of effort and resources. It was proposed that ESRO should choose between the various technologies available, using, to quote, "criteria to be defined by consultation between ESRO experts and Member States". It was, however, stated that *two* thrusters should be selected for further work.

In response to this initiative, the ESA Council issued a document in September 1975[4] in which it was stated that "it is highly desirable that the development of electric propulsion technology be pursued in Europe", primarily for nssk of 400 to 800kg satellites having a lifetime of seven years or more. Having reached this conclusion, it was decided to carry out a comparative study of the various competing systems, with the objective of selecting one, or possibly two, as being suitable for development to operational use on European communications spacecraft.

This study was delegated to the Attitude and Orbit Control Division of ESTEC, which has asked each interested national development agency to submit to ESTEC a comprehensive account of the developmental history, present status and future development plans of its candidate system.

The Report which follows represents part of the response by the UK to the request from ESTEC for information in May 1976; some mention is made of events and changes which have occurred since then, but no attempt has been made to bring the Report up to date fully. It mainly concerns the T4A electron bombardment mercury ion thruster, which has been developed jointly by the RAE, the UKAEA Culham Laboratory and UK Industry, with technical direction by the RAE and funding provided by the Department of Industry. However, when reference is made to

future development plans, later, improved versions of this device will be mentioned.

It is claimed in sections 1 and 2 that the performance so far achieved by the T4A thruster is exceptionally good in all important respects and that its durability should be entirely adequate for all likely nssk missions. In addition, the throttling ability of this thruster has been shown to be excellent and there is considerable evidence from the life-testing so far carried out that the thruster should not be harmful to other spacecraft systems.

The future development programme required to achieve a test flight at the end of 1980 and an operational flight in 1983 is given in section 3. It will be clear from this section that the technical objectives can be realised in the allocated timescales, provided that adequate funding is made available. No particularly difficult technical problems can be foreseen which would significantly impede progress, most of the remaining work being of a reasonably well-defined nature, and following technological routes which are already well-established.

1 TECHNOLOGY REVIEW

1.1 Introduction

The electron-bombardment mercury ion thruster described below has been developed by the UK over a number of years specifically for the north-south station-keeping (nssk) role on geostationary communications satellites. Although its operating characteristics have been optimised for that mission, it has proved extremely flexible, particularly as regards thrust level, so it is likely to prove suitable for many other purposes. The exceptionally good performance has been achieved partly by retaining a very flexible thruster design concept, and partly by the general philosophy adopted in the research and development programme. The flexible design concept includes such features as dual propellant flows to the discharge chamber, the use of electromagnets, and the use of a separate control loop which enables primary electron energy to be independently defined. These features have proved invaluable during optimisation of performance parameters, they allow degradation over long periods to be catered for without loss of mass utilisation efficiency η_m , and they also enable the thrust to be changed by at least a 2:1 ratio without mechanical alterations or significant loss of η_m . Competing designs, which do not possess this basic flexibility[2,5,6], may offer equally high performance under one set of conditions, but probably cannot maintain it as, for instance, those conditions change during a mission lasting many years.

The general philosophy during development has been to fully investigate, where feasible, the fundamental physical processes occurring in the thruster[7-9] or in its associated components[10,11] to obtain as complete an understanding of them as possible. In doing this, the primary aim has been to avoid the costly empirical experimentation phase often undertaken by other development teams. In this way, it was hoped to gather sufficient basic information to enable future designs to be produced with a good degree of confidence in their level of performance and durability. It can be claimed that this approach has met with considerable success, and that a competent design capability now exists in the UK.

As is normal in the development of a complex system, certain components must be defined almost completely before it is sensible to proceed far with other items. One such case is the thruster power conditioning unit (pcu). Although the appropriate design concepts were partially investigated as long ago as 1968[12], only later did the data necessary to design a realistic breadboard

system become available. This was designed, constructed and integrated with the thruster by MSDS Ltd.[13], and is now undergoing modifications in light of the more recent experience gained in operating the T4A thruster. In particular, it has been decided to use a microprocessor for all sequencing and control functions, rather than the previous hard-wired logic system.

A similar point may be made concerning the 'packaging' of the pcu for flight, with all its attendant redundancy, thermal, vibration and mechanical integration aspects. This exercise could have been started at an early stage of the development of the pcu, but such a procedure would have been wasteful of scarce resources; only in the event of an early flight would it have been justified, and much redesign would have been necessary later. Consequently, the 'packaging' work is only just commencing, the present start date being dictated by the need to meet a late-1980 test flight. One important consequence of this delay, which may be particularly beneficial, is that the work can take advantage of more modern techniques[14], which would not have been available in a proven form had the task been undertaken much earlier.

It should perhaps be stressed here that, in co-ordinating the UK project, every effort has been made to ensure that progress is founded on a broad technical base, with all likely problem areas receiving appropriate and adequate attention. The six organisations involved in the project (the RAE, the UKAEA Culham Laboratory, MSDS Ltd., HSD Ltd., Mullard Ltd. and the Fulmer Research Institute) are able to offer a very wide range of advanced technical expertise, which has been effectively combined to produce a highly efficient and durable thruster system.

Recently, the claimed expertise of these UK organisations in this field has been decisively confirmed by the outcome of an international competition for the supply and cyclic life-test of an ion thruster intended for the nssk role. An RFP was issued by Comsat[15] for this work in June 1975 and a bid was subsequently submitted by the UKAEA Culham Laboratory, which offered to supply a T4A thruster and to test it for 1500 three hour operating cycles. This test, which forms part of the UK development programme, was to include computer control of the cycling sequence and of the data acquisition and processing, and extremely comprehensive measurements of virtually all the materials emitted by the thruster. The latter requirement has necessitated the construction of a complex system of probes capable of separating, identifying and measuring particle fluxes composed of fast mercury ions, slow mercury ions, neutral mercury vapour,

sputtered material, and multiply-charged ions. The UK offer won the competition, although the contract was not placed subsequently due to funding cuts.

1.2 The T4A thruster

As described in section 2, the T4 thruster was designed jointly by the RAE and Culham specifically for the nssk mission, making use of the scaling laws[8,16] evolved at Culham from extensive physical studies of several fully instrumented electron bombardment thrusters of the Kaufman type[17]. The design thrust was 10mN and the exhaust velocity was chosen to be 30km/s, although it was recognised that both values might need to be altered later for particular missions.

The mechanical design of the thruster[18] was aimed at meeting the severe Black Arrow vibration specification (similar to that of the Scout launcher) and at minimising mass and the thermal interaction with a spacecraft. A further constraint was the need to include an integral propellant tank, to allow a single experimental package to be fitted to the spacecraft. In the event, the Black Arrow project was stopped, so an integral tank is no longer necessary and the Ariane vibration specification is now more appropriate.

Initial experimental work with the T4 device showed that its performance could be improved by a minor redesign of the discharge chamber and anode[19]. This increased the efficiency of ionisation by the primary electrons, raising η_m significantly. In addition, the plasma profile in the discharge chamber was much improved, increasing estimated grid life, while maintaining outstanding stability characteristics[20]. The thruster in this form was designated T4A, and most data given in this document were obtained from tests of this device. In particular, it has been the subject of most of the thruster life-testing done to date.

1.2.1 Operating principles

The UK ion thrusters have all been designed around the basic Kaufman concept[17], as used so successfully in the SERT II flight-test devices[21-23]. Many refinements and alterations have been included, however, and, as already mentioned, these provide improved performance, durability, and flexibility of operation.

A schematic section of the T4A thruster is shown in Fig.1, a section in Fig.2, and a photograph of one of the seven thrusters made in Fig.3. It consists fundamentally of a cylindrical discharge chamber in which a highly ionised

mercury plasma is produced by a dc discharge between an axial hollow cathode and a cylindrical anode. The ions from this plasma are removed and accelerated to a high velocity by a strong electric field set up between the two perforated and aligned grids forming the exit to the discharge chamber. The positive space charge of the emerging ion beam is neutralised by electrons emitted from an external hollow cathode.

To consider operation of the thruster in greater detail, it should first be mentioned that the mercury propellant is contained within a cylindrical stainless steel bellows housed within a pressurised cylindrical tank. Three mercury vapour feeds are required by each thruster, one direct to the discharge chamber, another to the hollow cathode mounted on the axis of the discharge chamber, and the third to the neutraliser. The valves used in the propellant pipelines are positioned to meet the operational and redundancy requirements of the mission in question.

Each liquid feed pipe terminates at a vaporiser[24], in which a porous tungsten plug acts as a liquid/vapour phase separator. The flowrate of vapour through this plug is determined by its temperature which, in turn, is a function of the power fed to the vaporiser heater.

The two vapour flows to the discharge chamber pass through electrical isolators, which allow the thruster potential to differ from tank or spacecraft potential by about 1kV in the case of a 30km/s exhaust velocity. These very small devices consist of porous alumina plugs sintered into alumina tubes[25]. Such a plug provides a large internal surface area which encourages electron-ion recombination and thereby raises the breakdown voltage at the minimum of the Paschen curve[26,27] from 400V to about 4kV.

The hollow cathode is designed to produce the electrons required to ionise the propellant with high efficiency, and to have a long life. It consists of a tantalum tube into one end of which is welded a tungsten disc having a small central orifice[10,28]. The tube is surrounded by a heater and heat shield assembly, and it contains a dispenser of a low work function material, principally barium. In operation, an internal plasma is created from the mercury vapour fed to the cathode[10], and a current of electrons is drawn through the orifice by an electric field set up between the external keeper electrode and the internal plasma. The internal emission is not yet fully understood, but it appears to be predominantly due to field-enhancement of a thermionic current produced by the high temperature and partial barium coverage of the internal

surfaces[10,29]. A further important mechanism may be the secondary emission of electrons due to the bombardment of internal surfaces by metastable mercury atoms.

The heater is normally employed only for discharge initiation, when a high temperature and a high keeper potential are required to start emission from the cathode. During steady operation, the cathode is heated by ion bombardment from the external plasma.

The ions, electrons and neutral atoms emerging from the cathode orifice constitute the coupling plasma (Fig.1), which has a relatively low degree of ionisation and a low electron temperature. This plasma fills the space bounded radially by the inner magnetic pole and axially, downstream, by the baffle disc. The primary electrons are extracted from this plasma through the annular gap between the pole and disc. In being extracted through this gap, these electrons gain energy[9]; the design of this critical region of the thruster is optimised to ensure that this energy is of the correct value to give highly efficient ionisation, whilst preserving a flat plasma density profile near the grids[20]. As well as the geometry, the parameters important in determining the flux and energy of the primary electrons include the cathode vapour flow rate, the electron temperature in the coupling plasma, and the exact form of the magnetic field distribution at the tip of the inner pole.

Once they have emerged into the discharge chamber, the primary electrons are constrained from reaching the positive anode by the magnetic field between the inner and outer poles. They are obliged to gyrate around the field lines, moving from the edge of the plasma sheath in the vicinity of one pole to the equivalent sheath at the other, until they suffer collisions with other particles, which allow them to migrate towards the anode. Electron-atom collisions both excite and ionise the mercury vapour fed into the discharge via the cathode and via the annular distributor of the main flow system. The design of the discharge chamber and of the magnetic circuit[8,19] ensures that the ionisation process is efficient, that the plasma density profile is comparatively flat, and that the discharge is very stable. This state of affairs is maintained over a very wide range of thrust.

The ions drift towards the grid system under the influence of a density gradient and the magnetic field shape and strength. On reaching the edge of the plasma sheath at the screen grid, they are immediately accelerated through matching pairs of holes by the high electric field applied between the screen

and accelerator (accel) grids, thereby forming an energetic ion beam. The use of a thin screen grid and of a high open area ratio ensures that the extraction efficiency is high, giving an excellent perveance[28].

The grids are dished inwards to provide thermal stability[18,28] and are designed to give a low beam divergence, while minimising direct ion beam impingement and erosion from sputtering by charge-exchange ions. The desired divergence is achieved by positioning the holes in the accel grid so as to direct the ions electrostatically into the required directions; this is termed 'compensation', because it partially offsets the tendency for the beam to focus near the grids due to the spherical dishing[30]. The use of low accel grid potential, the uniform plasma density profile, and the high value of η_m attained by the thruster all contribute towards the low sputtering of the accel grid[31].

The neutraliser cathode is almost identical to that fitted to the discharge chamber, except that it has a larger orifice and its keeper electrode assembly is joined to it by brazing. The vaporiser supplying it with mercury vapour is separated from it by a short alumina tube, termed an insulator, which allows the two components to be maintained at slightly different potentials. The cathode can thus be biased relative to spacecraft potential[32]. In operation, a cathode-keeper discharge is set up at a very low mercury flow rate[33]. Electrons are then attracted to the beam from the resulting plasma in sufficient numbers to exactly neutralise the positive space charge of the beam. This is a self-regulating process, any over- or under-neutralisation being compensated for, on a micro-second timescale, by an appropriate change of the potential difference between the beam and the plasma. It should be noted that the severe local grid erosion caused in the SERT II and other thrusters by the neutraliser has been eliminated in the T4A by careful positioning, by the use of a very low neutraliser flow rate, and by reducing the accel grid voltage by an order of magnitude.

The whole device, except the working area of the accel grid and the tip of the neutraliser system, is surrounded by a metallic screen, which prevents electrons from being attracted to the positive thruster. The dimensions, emissivity, material and open area ratio of this screen may be used in the thermal control of the thruster.

1.2.2 General design and constructional features

The essential features of the design of the T4A thruster are shown in Figs.2 and 3. The beam extraction grids are mounted on the iron front pole, and axial loads resulting from the mass of the grid/pole assembly are resisted by the six solenoid cores, which are used as structural members. Solenoids were chosen to generate the magnetic field within the discharge chamber because they offer flexibility of operation. The cylindrical stainless steel discharge chamber is bolted to the backplate, but is not attached to the front pole, thus permitting differential expansion between itself and the front pole and solenoids. The thin cylindrical stainless steel anode is mounted from the discharge chamber by three suitably sputter-shielded alumina insulators. The dimensions of the discharge chamber, the inner pole/baffle assembly, and other components influencing the production and behaviour of the plasma or ion beam were derived from the scaling laws formulated by Culham[8,16].

Most of the remaining components are bolted to the iron backplate, to which is also brazed the nickel-sheathed heater used during start-up sequences. The solenoid cores transmit loads from the front pole/grid assembly to this backplate, and thence to the tubular support structure. Components fixed to the backplate within the discharge chamber include the iron inner pole and tantalum baffle disc, the latter being supported from the pole by three legs and a small central screw. Surrounding the cathode pole is an annular stainless steel main flow distributor. Holes are provided in its inner curved surface to allow mercury vapour to enter the discharge chamber in a radial direction.

The upstream face of the backplate carries the hollow cathode/isolator/vaporiser assembly and the main flow isolator/vaporiser assembly. The cathode is attached to the backplate via a stainless steel mounting flange to which are also welded the keeper support insulators. The latter are identical to the anode insulators, consisting of alumina tubes brazed to suitable Kovar flanges, with appropriate sputter shielding. The thin cathode mounting flange is designed to minimise the heat loss from the cathode assembly to the backplate.

The main flow assembly is terminated in a stainless steel flange which bolts directly onto the backplate. As shown in Fig.2, this flange contains a right-angle bend, so that the isolator and vaporiser lie parallel to the face of the backplate. An alternative design has also been used, in which the flange is straight, causing the assembly to be parallel to the thruster axis.

In Fig.2, the propellant tank is mounted at the rear of the stainless steel tubular support structure. This configuration was designed specifically for the Black Arrow X5 satellite project, and will not be used in future applications, where it is envisaged that two interconnected tanks will probably be employed to feed all thrusters mounted on a spacecraft. The resulting redesign of the thruster's support structure is described in section 1.6.

The main mounting insulators are made from alumina and are brazed to Kovar flanges. Sputter shields are provided. In the T4A design, they are situated at the rear end of the support structure.

The whole thruster is surrounded by a thin stainless steel earth screen. This is carefully shaped at the accel grid to avoid direct ion impingement; it is not perforated in this region. However, perforations may be provided along most of the cylindrical length of the screen to assist in adjusting the heat balance of the installation, the open area ratio being up to 50%. Tests conducted with both completely opaque screens and an open area of 50% have shown that the former type increases all thruster temperatures to some extent and reduces the rate of fall of temperature following switch off, but neither change is detrimental to the overall performance.

The neutraliser assembly is mounted from the front pole via an insulator, with additional support being provided at the backplate, again via an insulator. A hole is cut in the earth screen to allow the neutraliser to protrude approximately 2.5cm beyond the plane of the accel grid.

1.2.3 The hollow cathode assembly

The hollow cathode used in the T4A thruster was designed following extensive experimental investigations at both the RAE and Mullard Ltd.[10,34,35], including life-tests to over 5000 hours duration.

The cathode/isolator assembly is depicted in section in Fig.4. The cathode consists of a tantalum tube of 3.2mm outside diameter into one end of which is welded a 1mm thick tungsten disc having a central parallel-sided orifice. Surrounding the downstream end of the tantalum tube is a bifilar heater made from 0.2mm diameter split-free tungsten wire encapsulated in flame-sprayed alumina. The alumina is separated from the tantalum by a thin layer of tungsten, which is either plasma-sprayed or sintered from a powder form. The tungsten acts as a barrier and prevents chemical reactions from occurring between the alumina and tantalum at elevated temperatures[36]. The outer surface of the alumina is ground

to a diameter of 6mm. The heater resistance is about 0.7 ohm when cold, increasing to about 5 ohms with a cathode tip temperature of 1100°C.

The tungsten leads to the heater are sheathed with tantalum tubes, which are anchored in the final alumina coating, to ensure that they are of relatively low resistance and temperature. These coaxial tungsten/tantalum leads are terminated and joined to 0.5mm diameter molybdenum wires before emerging from the rear flange of the cathode assembly. These wires pass through the flange in alumina tubes which are brazed into position, and finally terminate on insulators fixed to the cathode mounting flange.

The complete assembly is surrounded by a stainless steel tube of 11.5mm outside diameter, which is welded to the Kovar rear flange. Between this tube and the heater is positioned a multi-turn radiation shield system, which is constructed from many turns of dimpled molybdenum foil, and which was designed following extensive testing[28]. The tip of the cathode protrudes through a central hole in a stainless steel disc welded at its periphery to the end of the outer tube. Between this disc and the multi-turn radiation shields is situated a stack of disc-shaped shields, which minimise axial radiation losses. The excellent thermal performance given by this assembly is illustrated in Fig.5, from which it can be seen that a tip temperature of 1000°C is reached with a power input of only 8.6W.

Cathodes used in the early phases of the T4 thruster project incorporated rolled foil dispensers of low work function materials[10], but these were later replaced with porous tungsten dispensers[35,37]. This change gave three advantages: greater potential resistance to damage from launch vibration, improved manufacturing reproducibility, and a larger content of emissive material. The latter is barium-calcium-aluminate, and the porous tungsten is impregnated with it in a carefully controlled high temperature process. Reproducibility is checked by weighing, and detailed examinations of such dispensers by electron beam microprobe techniques have confirmed that impregnation is very uniform[36].

The discharge performance of cathodes having these porous dispensers is excellent, and tests of up to 4000 hours duration have indicated that degradation, as judged by the rate of rise of plasma potential, is very slow. In fact, this degradation is less marked than with roll foil dispensers, and these have been successfully tested in this programme to 5000 hours[20,35]. It has been established that the most important cause of the decrease of performance of a

cathode over a long period of time is the loss of the low work function material from the dispenser[36]. This loss is minimised in the present design by keeping the operating temperature reasonably low; for this reason, the cathode orifice is relatively large and heater power is applied only during start-up. The low discharge current required by the thruster is also of assistance in this context.

The tantalum keeper is situated about 1.5mm from the cathode tip and is supported by sputter-shielded insulators from the cathode mounting flange. The diameter of its orifice is 3mm, but this has been shown to be a non-critical parameter. The keeper is used in the discharge initiation process, a high dc voltage being applied to it while tip temperature and flow rate are both increased. It has been shown experimentally that this is a satisfactory technique, provided that the three critical parameters are correctly adjusted[10,35].

1.2.4 Isolators

In any satellite installation of an ion thruster system, it is essential for the propellant tanks and pipelines to the thrusters to be at spacecraft potential if inconvenient high voltage problems are not to arise during thruster/spacecraft integration. Owing to the fact that the bodies of all ion thrusters operate at high potential (nearly 1kV in the case of the T4A), it is necessary to incorporate electrical isolators in the vapour feed lines to achieve the above aim.

In the T4A thruster, two alumina isolators are used. One is brazed to the rear flange of the cathode assembly (Fig.4), while the other is brazed between the main flow vaporiser and the flange bolted to the backplate (Fig.6). They are identical, and both are fitted with heaters and with radiation shields, which also act as sputter shields. The cathode isolator is shielded from the plasma within the cathode body and from UV radiation by a porous stainless steel disc situated between the isolator and cathode.

The isolators were developed by the RAE[25,28], and manufacturing processes were devised by Anderman and Ryder Ltd. Their small size (30mm long, 11mm diameter) is a most attractive mechanical feature, and results from the use of a novel approach in their design. Basically, a 3mm diameter porous alumina structure within an outer finned tube provides a large internal surface area which encourages electron-ion recombination and thus inhibits electrical breakdown. It can be seen from the experimental data in Fig.7 that the minimum breakdown

voltage is a function of the size of the spheres forming the porous structure. It is clear that the use of small spheres raises the minimum voltage very substantially; the value of this parameter for the isolators fitted to the T4A thruster is between 4 and 5kV, at an internal pressure of about 30 torr.

As reported recently[20], some degradation of both leakage current and minimum breakdown voltage occurs over long periods of time. However, it was shown that external contamination by the constituents of stainless steel sputtered from the test facility and from the thruster caused the measured increase in leakage current. Cleaning the external surface mechanically reduced the leakage at 2600 hours in a diode test from 0.5mA to below 1μA. The isolators tested on this and other relevant occasions were not fitted with radiation or sputter shields, and the provision of these reduces the problem by orders of magnitude. This has been confirmed in a 1000 hour thruster test, in which the leakage resistance of each isolator did not fall below 500MΩ with the application of 1kV. In addition, the degradation of breakdown voltage is not serious, as a large safety margin is available. There is also evidence that it may be caused, at least in part, by the deliberate diagnostic breakdowns initiated at regular intervals throughout the various reported life-tests.

The isolator heaters are made from nichrome wire encapsulated in alumina and have a resistance of about 8 ohms. Robust terminations are provided in the cathode isolator by passing Kovar pins through small diameter alumina tubes which are brazed into the heat shield support flange (Fig.4). The terminations to the main flow isolator heater are carried by tubular glass to metal seals attached to the small support bracket (Fig.6).

The cathode isolator heater is situated on the flange brazed to the upstream end, heat fed back from the cathode keeping the other end warm. It is therefore at satellite potential. The heater on the main flow isolator is placed on the flange brazed to the downstream end, which tends to be cooler owing to its contact with the backplate, which is at thruster potential. In both cases, the aim is to prevent mercury vapour condensation, especially during rapid starts. Typical operating temperatures are between 250 and 280°C; the temperature distribution along the cathode/isolator/vaporiser assembly is shown in Fig.8.

1.2.5 Vaporisers

Three almost identical vaporisers are used in the thruster to provide two mercury vapour flows to the discharge chamber and a third to the neutraliser. Typical flow rates are 0.16mg/s to the cathode, 0.24mg/s to the distributor and 0.01mg/s to the neutraliser.

The basic vaporiser, which was developed by the RAE[11,24], is very small, but conventional in operation. It consists of a 1mm thick porous tungsten plug electron-beam welded into a 5.5mm outside diameter tantalum tube (Fig.6). The 3.2mm diameter plugs are of closely controlled porosity (about 1.5%) and the permeability is reproducible to about ±7%. Weld penetration is closely controlled and does not significantly increase this scatter of permeability. The porosity and the working areas of a plug are selected to enable the correct mercury vapour flow rate to be achieved at approximately 280°C, although this is not in any way a critical parameter. The plugs are capable of withstanding much higher pressures than the 2 bar pressurisation proposed for the mercury tank (section 1.4.1); a typical breakthrough pressure is about 6 bar.

The external single coil heater is made from nichrome wire encapsulated in alumina. It has a resistance of 14.5 ±0.5 ohm, to be compatible with the pcu, and its outer diameter and length are 9.5mm and 16mm. The heater wire is joined to 0.6mm diameter nickel or Kovar leads, which pass through alumina tubes held by Kovar termination straps welded to the flanges on each end of the tantalum body.

The upstream stainless steel end cap nearest the porous plug is identical in each vaporiser, as it is always welded to a 1.5mm outside diameter stainless steel liquid mercury feed tube. The cap at the downstream end is identical in the cathode and neutraliser vaporisers, because these are also connected to the next components by 1.5mm diameter tubes. In the case of the main flow vaporiser, however, a 5.5mm diameter thin-walled tube is employed, which is welded directly onto the tantalum body (Fig.6). The dimensions of these connecting tubes are chosen to ensure that temperatures are everywhere adequate to prevent mercury vapour condensation. Typical temperature distributions along the cathode/isolator/vaporiser assembly are shown in Fig.8.

The heat loss from any vaporiser is mainly by radiation from its alumina-coated heater, unless the emissivity of this is reduced by covering it with a low-emissivity layer of molybdenum foil. In addition, conduction occurs along the connecting tubes and through any mounting flanges employed. These two loss mechanisms are adjusted so that the cathode and main flow vaporisers operate under steady state conditions with a power input of 2 to 4W; about 1W is supplied to the neutraliser vaporiser. By careful design, much lower inputs can be achieved, but reasonably large losses are necessary to obtain cool-down rates suitable for closed-loop operation[38]. Fast start-up is easy to achieve, because

the heater will tolerate the high power inputs necessary to give rapid increases of temperature; 12 or 15W may be used if necessary, although the pcu currently supplies up to 10W.

The vaporisers are extensively tested during and after manufacture, and great care is taken to ensure that all parts are free of contaminants which may cause wetting or blocking of the tungsten plugs. The testing process involves three stages:

(a) gas flow calibration to check that the plug permeability is suitable;

(b) gas pressurisation of a head of liquid mercury held back by the plug, to check that it is not defective and does not leak;

(c) an accurate mercury vapour flow calibration, with flow rates measured to ±1%, to check for reproducibility and overall performance. Power levels are also assessed.

1.2.6 <u>The neutraliser system</u>

This consists of a hollow cathode/keeper assembly, which is brazed to an alumina insulator to which is joined a vaporiser (Fig.9). Apart from a larger orifice[33], the cathode is identical to that used in the discharge chamber. The keeper is brazed to an alumina cylinder, which is brazed at its upstream end to a flange welded to the outer tube of the cathode assembly. A major aim of this design was to minimise the possibility of keeper-cathode shorts due to the deposit of sputtered materials on the internal surfaces of the keeper insulator. For this reason, a narrow gap is provided between the alumina cylinder and the outer tube of the cathode assembly. The effectiveness of this technique has been demonstrated in a 1000 hour thruster test, at the end of which the keeper-cathode impedance at 1kV was 10000MΩ.

The rear flange of the cathode assembly is brazed to a short tubular insulating section, which is provided to allow the neutraliser to operate at other than spacecraft potential. This alumina insulator is not fitted with a heater, because thermal energy conducted from the cathode is adequate to prevent internal mercury condensation. The insulator is connected via a brazed-on Kovar flange and a short length of 1.5mm diameter stainless steel tube to a standard vaporiser. As in the other vapour feed systems, this pipe provides a measure of thermal decoupling, and allows the vaporiser temperature to be changed relatively quickly.

The neutraliser assembly is mounted at two points. The rear of the cathode is supported from the front pole of the thruster by an alumina insulator and the liquid mercury feed pipe leading to the vaporiser is similarly supported from the thruster mounting structure. A sputter shield assembly surrounds the keeper insulator.

As with the main cathode, the neutraliser discharge is initiated by the application of a high voltage dc supply to the keeper, which is positioned about 1.5mm from the cathode tip and has an orifice of 3mm diameter. Although it is necessary to provide a higher flow than normal to achieve a discharge, the propellant used in this process is only a very small proportion of that needed during an operational cycle. In addition, the beam is not being extracted during this phase of the start sequence, so there is no additional charge-exchange damage to the accel grid (section 1.5.13), because the voltage responsible for accelerating low velocity ions to the grid has not yet been applied.

1.2.7 Ion extraction system

As can be seen in Fig.2, the twin molybdenum grids are dished spherically inwards to provide mechanical stability and to minimise changes in the inter-grid separation due to temperature variations. It was found by experiment[28] that the dishing depth chosen, 6mm, reduces such changes to less than 0.1mm, which is about 7% of the value measured for flat electrodes. The radius of curvature is 23.3cm. The screen grid is 0.25mm thick, while the accel grid has a thickness of 0.75mm.

The dimensions of the circular ion extraction apertures were selected by reference to the thruster scaling laws formulated by Culham[8], the screen grid having 2.15mm diameter holes and those in the accel grid being of 1.75mm diameter. Thus the geometrical open area ratio τ is about 70% for the screen grid and 46% for the accel grid. The 1573 holes form a hexagonal array and cover a working area of 10cm diameter; this dimension effectively defines the size of the thruster. The hole centres are nominally separated by 2.46mm. The holes are best produced by spark erosion[39] after dishing and heat treatment, so their axes lie parallel with the thruster axis.

As shown in Fig.2, the accel grid is insulated from the screen grid by a ring of six sputter-shielded alumina insulators which define the electrode spacing at 0.75mm when cold. The grids are attached to the front pole of the thruster by means of six compliant strips, which permit differential radial

thermal expansion between the grids and the front pole, whilst maintaining accurate alignment of the axes of the hole arrays.

As also found in other ion thrusters with dished grids[5,40], if the same hole spacings are provided in both the screen and accel grids, each individual beamlet is deflected from the ideal paraxial direction by both the simple curvature of the grid system and by an associated electrostatic effect. The latter[30] deflection is due to the fact that each pair of screen and accel apertures are aligned axially, rather than along a radius of curvature. With concave dishing, as on T4A, this causes each beamlet emerging from a screen hole to encounter an accel hole effectively displaced outwards, thereby producing a force directed radially inwards. As shown in Fig.10a, this amounts to an inward deflection of about 7°, causing the whole beam to be focussed more strongly than expected on geometrical grounds alone. The focal point is 14cm from the accel grid, and the overall effect is of convergence followed by divergence, giving a 'waisting' appearance. A half angle ϕ of 17° contains 95% of the beam current I_B.

In order to reduce ϕ, the positions of the holes in the accel grid may be changed slightly with respect to those in the screen grid, to produce electrostatic vectoring of up to about 10° without direct ion impingement on the accel grid[30]. Two different displacements or 'strains' have been tested to 1000 hours on the T4A thruster, with excellent results in both cases, As shown in Fig.10, the compensation introduced by the 1% strain grids gives the better beam divergence, 95% of I_B being contained within 7.7°, as compared to 10.3° for 0.5% strain, but the former grids receive some direct ion impingement in peripheral holes where significant aberration occurs and the electrostatic deflection is greatest. Consequently, the 0.5% strain configuration has been selected for future thrusters.

The ion extraction performance of these grids is excellent, and closely corresponds with that predicted by the scaling laws. In particular, the design objective of achieving an effective screen open area ratio substantially greater than the geometrical ratio was realised. This was accomplished through utilising the additional ion emitting area provided by the curved plasma sheath at each screen aperture, and gives an effective τ, corrected for peripheral losses, of 80%. Thus the ion extraction efficiency is considerably improved and, conversely, losses of energy and propellant through recombination at the surface of the screen grid are reduced. The perveance, measured for beam currents in the range 80 to 200mA, is about $2.4 \times 10^{-6} AV^{-3/2}$.

The accel grid voltage V_{ac} necessary to provide focussing and to prevent electron backstreaming from the neutraliser plasma has been reduced substantially below the initial value of 600V. As an example, Fig.11 shows the accel voltage-current characteristic for the 0.5% compensated grids tested to 1000 hours by the Fulmer Research Institute (FRI). A broad minimum exists between V_{ac} = 300 and 400V, with an accel grid current below 0.5mA, that is below 0.3% of the beam current.

1.2.8 Discharge chamber sputtering

Although a high rate of sputtering within the discharge chamber can be a problem with Kaufman mercury ion thrusters[41], several methods are available to minimise this phenomenon and to overcome the difficulties associated with it. Three of these techniques have been employed in the design of the T4A thruster, with excellent results.

The most obvious precaution is to manufacture those components most susceptible to sputtering from materials having a low sputter yield, such as tantulum and molybdenum. As the part most at risk appears to be the baffle disc[41], it is fabricated from tantalum. Similarly, for this and other reasons, the grids are made from molybdenum.

Much of the material produced during the sputtering process is deposited on the internal surfaces of the discharge chamber. However, there will be a tendency for it to be re-sputtered from those components at cathode potential and for it to accumulate on items at higher potential, such as the anode. It is the flaking away of such deposits from the underlying surfaces that causes difficulties by, for example, electrically shorting the ion extraction grids together. Methods of improving the adhesion of these deposits have been extensively studied at Culham and a roughening technique has been selected, which is used to treat all internal surfaces of the T4A thruster. As well as giving considerably better adhesion, it also causes any flakes that might become detached to be small enough to avoid shorting problems. A similar approach has been adopted elsewhere[42].

The third method employed to alleviate the sputtering problem is more fundamental because it involves an appreciation of the physical processes responsible for the observed effects. It is generally recognised that the particles responsible for most of the sputtering are doubly-charged ions. These are probably produced by further ionisation of singly-charged ions[43], the

rate of formation in any region being determined by the ion and electron number densities and the energy of the primary electrons. In the T4A thruster, the rate of production of doubly-charged ions has been minimised by reducing the primary electron energy to the lowest value compatible with the attainment of high values of η_m . This, together with the achievement of a comparatively flat plasma density distribution, enabled localised peaks of doubly-charged ion production[41,47] to be avoided. Consequently, this thruster operates at a relatively low anode potential, whilst achieving a high value of η_m and minimising internal sputtering damage due to doubly-charged ions, unlike many other thrusters, which require high anode potentials to achieve similar utilisation efficiencies. They therefore suffer from severe internal erosion, and also highly peaked plasma density profiles, with resulting concentrated accel grid erosion.

1.3 The power conditioning unit

As mentioned previously, although extensive work had been done as early as 1968 on many of the basic concepts likely to be used in an ion thruster pcu[12], it was not considered a sensible use of resources to commence fullscale breadboard development until the majority of the thruster operating parameters were properly defined. Consequently, pcu design, development and production has deliberately lagged behind the equivalent work on the thruster itself. However, as shown in section 3, there should be no difficulty in meeting the flight target dates specified by ESTEC, assuming that appropriate funding is made available.

At the time of writing, a breadboard pcu[13] has been designed and constructed by MSDS Ltd., and a considerable amount of experience has been gained in integrating this system with T4A thrusters at both Culham and the RAE. The pcu contains the power supplies necessary for thruster operation (Fig.12), together with a start-up and recycle sequencer, analogue control loop electronics, and a complete set of telemetry output channels. It is therefore completely self-contained, requiring only input power and commands to operate the thruster.

Experience gained with the T4A thruster since the first design of the breadboard pcu was completed has indicated the desirability of certain changes, mainly concerning the start-up sequence. As a result, the breadboard system will be modified before being tested again with the thruster. The design of the flight packaging system will start in parallel with this activity; details of this programme of work are given in section 3.

1.3.1 Operating principles

As indicated in Fig.12, the thruster requires 12 individual power supplies for its normal operation and, in addition, three further supplies for the isolator and backplate heaters used during the start-up procedure. However, the latter are provided by three auxiliary outputs from the discharge supply, so additional modules are not needed. The modular power conditioning unit developed[13] to meet these requirements and to control the operation of the thruster during start-up and under steady-state conditions is shown schematically in Fig.13. It employs pulse-width modulated (pwm) circuitry, with phase-staggering to ensure that the load placed on the satellite's battery or solar array is reasonably constant in time.

Particular emphasis has been placed upon developing the specialised circuit techniques required to operate at high efficiency in a realistic environment, and the type of components used are those which can be obtained with space-qualification status. The configuration of the supplies within the conditioner minimises the number of sensitive circuit elements referenced to the beam supply potential of 900V, so that the risks of device breakdown are considerably reduced.

There are two modes of operation; with the supplies under individual manual control or operated automatically by sequencing command logic and analogue engine control loops. The sequencing and control logic monitors several thruster parameters which are compared with preset limits and so determine whether the start-up and running conditions are normal. If they are not, corrective control routines are undertaken to restore the desired engine status. All voltages and currents are also monitored for telemetry purposes.

The three thruster flow rates are regulated by the control loops to keep the beam current, the energy of the primary electrons, and the neutraliser keeper voltage at preset constant values. Cross-coupling terms between these loops are taken into account in shaping amplifiers. During the automatic start-up sequence, logic commands override the control loops and set the vaporiser supply outputs to pre-determined levels to give the desired start-up time and minimise settling time when control is restored.

The present pcu employs a hard-wired logic system to control the start-up and shut-down phases of operation, and to monitor behaviour during thrusting. It is now intended to take advantage of the much greater flexibility offered by

a microprocessor, and such a device will be used for these functions in future versions of the pcu. Consequently, if alterations are required to, for example, the start-up sequence to achieve a different start-up time, they will in future be capable of implementation through changes to the 'software' only. In addition, greater precision will be attainable in shaping current and voltage waveforms during this sequence, and throttling, if required, will be facilitated.

1.3.2 The power modules

The pwm power supply modules operate at 18kHz, this frequency being chosen to minimise the sum of power transistor and transformer losses, the ratings of these components allowing over 55W to be delivered per individual module output. The characteristics of the various modules used are detailed in Table 1.

An endeavour has been made during the design phase to maximise the number of features common to all modules; this aim has been substantially realised, even though many different voltage and current levels are supplied, some dc, some dc in pwm form and some ac. Although the efficiencies of individual modules depend on many parameters and may be measured and interpreted in more than one way, they are very high. The recorded values include 89.5% for the beam supply, 87% for the discharge supply, and 93.7% for the vaporiser supplies. The efficiency of the overall system is not far short of 90%.

The method of pulse width modulation is similar for all modules, and makes use of standard TTL integrated circuits. A 36kHz waveform is modulated using a monostable, controlled by an analogue or set point input voltage. This waveform acts upon two antiphase 18kHz inputs such as to impress the modulation on them, and the resultant is power amplified. The system is shown in block diagram form in Fig.14.

For all but the directly-coupled three vaporiser supply module, a push-pull current from a +56V supply flows in the output transformer, is rectified and filtered to suppress unwanted ac components where necessary, and is fed to the appropriate thruster load. The power amplifying stage incorporates a dynamic current drain circuit to remove unwanted charge stored in the output transistors. Fig.15 shows the improvement brought about by this feature. The modulation system permits a modulation index of between 0.1 and 0.90, the latter limit being introduced to exclude the possibility of cross-over modulation causing overheating and possible failure. In the case of the three vaporiser supply module, power from a +12V source is supplied in pwm form, at 6kHz, directly to the 14.5 ohm vaporiser heating elements.

Table 1

Characteristics of pcu power modules

Module designation	Nominal output voltage	Nominal output current (amps)	Output classification	V or I data outputs, data in range -5V to +5V	Reference potential*	Other output information
Discharge anode	40	1.2	dc	V, I	HV	Internal current feedback for constant current operation. External voltage feedback to form part of Loop 1 error signal. Also supplies thruster preheaters during thruster early warm up.
Beam (HV)						Internal voltage feedback
Master	300					Internal current feedback for protection
Slave 1	300	0.167	dc	V, I	S	External current feedback to form Loop 2 error signal
Slave 2	300					
Accelerator grid	-300	0.4mA	dc	V, I	S	Internal current feedback for protection. 5-10mA capability during switch-on, or arcing
Magnet	16	0.3	dc	I	HV	Internal current feedback for constant current operation
Discharge hollow cathode heater	9.5 (max)	2.9 (max)	ac (pwm)	I	HV	Output rate of rise controlled during thruster start-up. Off when thruster running
Neutraliser hollow cathode heater	9.5 (max)	2.9 (max)	ac (pwm)	I	N	Output rate of rise controlled during thruster early warm-up. Off when thruster running
3 vaporiser supply	8.6	0.5	dc (pwm)	V (3 off)	S	Control inputs from Loops 1, 2 and 3 cause modulation of outputs Higher voltages and currents for starting
Neutraliser bias	25	0.167	dc	V, I	S	Voltage chosen depends on requirements of the mission. Internal voltage feedback for constant voltage operation
Neutraliser keeper Trigger	24 600	0.3 0.3mA	dc dc	V (start) V, I	N	Internal current feedback (0.3A) for constant current operation External voltage feedback to form Loop 3 error signal
Discharge keeper Trigger	13.5 600	0.4 0.3mA	dc dc	V (start) V, I	HV	Internal current feedback (0.4A) for constant current operation External voltage feedback to form part of Loop 1 error signal

* Reference potentials: S = spacecraft/earth, N = neutraliser bias, HV = beam supply output

Phase staggering, which has the effect of reducing the magnitude of switching transients, is employed, and allows a reduction in the mass of filter components.

The philosophy of maximising the number of features common to all modules has enabled costs to be kept down during the breadboard phase of development but, more importantly, should greatly aid conversion of the system to flight status. Both the input stages and power amplifying stages lend themselves to ready conversions to thick film hybrid form[14], without the necessity of having to produce a large range of circuits. With regard to discrete components, the breadboard system has used, so far as possible, components which have attained flight qualification status, or their commercial equivalents.

It is necessary in the case of most modules to feed back data regarding output current, or voltage, in order to establish a particular mode of operation; for example, the discharge and keeper supplies operate in a constant current mode. Data has, in many cases, to be transferred across a high voltage interface in order to apply feedback to an 'earth' referenced module input. Furthermore, during a flight it will be necessary to transmit back to ground output voltage and current data or possibly to supply an on-board computer with information[44]. To meet the above requirements, current and voltage monitoring circuits were developed which, with a minimum of high voltage referenced components, transfer the necessary data accurately across the high voltage interface. These circuits have been extensively used, and satisfactory performance has been obtained as regards accuracy, durability and stability.

The typical monitoring circuit shown schematically in Fig.16 is used to transfer measurements of discharge or keeper current across the high voltage interface, from thruster to spacecraft potential. In this circuit, the signal generated by feeding the current of interest through a small-value resistor is chopped by a square wave applied to a field-effect transistor (FET). The resulting current pulses are fed to the primary of an isolating transformer, with a minimum of 2kV primary to secondary insulation. The output from the secondary is passed to a signal processing circuit, again using FETs for power economy. An amplification stage then follows, which gives an output with a maximum value of 5V. The power consumption of these signal transfer circuits is very low. For instance, the discharge current circuit when measuring 1A consumes 0.5W, including the loss in the series sensing resistor, and the keeper current sensing circuits consume 60-80mW. Accuracy is excellent, the discharge current

circuit achieving ±1% from 0.8 to 1.2A over a wide temperature range. As shown in Fig.17, linearity is also good.

A two stage protection system is used to guard the beam and accelerator power supplies against the short-circuit conditions that would exist if a thruster grid to grid arc occurred. The first stage cuts back the beam supply output, which is normally of about 160W, such that a short circuit current flows that is only about 20% above normal. This is achieved by operating in a 'burst' firing output mode in which not only is the pwm cut back to a minimum, but, additionally, an inhibiting system is brought into operation which allows trains of defined length of these pulses to be followed by OFF periods. By these means, output power is limited to 6W. In the case of the accelerator supply, which normally provides 1.8W, the first stage of protection is quite adequately achieved by current limiting.

Second stage protection is invoked if the arc condition persists (at present, a duration of >5ms is regarded as persistent). In this case, the sequencer supplies a 'high voltage shut-down' command, followed about 2 seconds later by a 'reset' command. If repeated excursions around this loop fail to remove the arc, the thruster is then completely switched off. Later a normal re-start sequence is initiated.

1.3.3 The sequencer

The start-up and recycle sequencer provides a pre-set switching programme that is a function of both time and of thruster status. An example of the type of procedure it is designed to follow is shown in Fig.18, which is a simplified version of the programme currently provided by the hard-wired sequencer in the breadboard pcu.

Under conditions of a normal start from cold, the sequencer initially turns on the backplate and isolator heaters, it being necessary to preheat the vapour feed lines, isolators and discharge chamber to prevent condensation of mercury vapour. After a set delay, several other supplies are turned on, including the cathode heaters. On attainment of the correct temperature, the vaporiser power supplies are turned on, not necessarily simultaneously, and mercury vapour begins to flow into the thruster and the neutraliser. The exact times of turning on these supplies and the rates of rise of temperature of the three vaporisers are adjusted so that the neutraliser discharge is the first to be initiated. If this discharge does not commence within a specified time, a correction sub-routine is used to increase the neutraliser flow rate, which promotes easier starting[10], but increases the propellant loss.

Once the neutraliser discharge has been satisfactorily established, with the keeper current within acceptable limits, the neutraliser cathode heater is turned off, the vaporiser heater current is restored to normal and, after a delay, the neutraliser control loop is closed. By about this time, a discharge will have started between the discharge chamber hollow cathode and its keeper electrode. The application of the anode voltage then causes the main discharge current to flow. If either of these actions do not occur within a specified time, correction sub-routines are commenced. If there is no discharge to the keeper, the power to the hollow cathode vaporiser is increased to produce a higher flow rate, whilst if the keeper discharge is satisfactory, but there is no current flow to the anode, the magnetic field is altered.

Once the main discharge is satisfactory, all remaining pre-heaters are turned off and the cathode vaporiser heater current is returned to normal. After a delay, the beam and accel supplies are turned on and, assuming that operation is within specified limits, the remaining two control loops are closed. If abnormal conditions are sensed, further correction sub-routines are used. In the event of excessively high beam or accel currents, an arc between the grids is diagnosed and a switch off/recycle routine is followed. If the beam current is very low, the implication is that the discharge has been partially or completely extinguished, so the sequencer returns to the beginning of the programme.

During steady operation of the thruster, the sequencer remains quiescent, unless certain out-of-limit behaviour modes are detected. It then initiates remedial sub-routines. For example, should an inter-grid arc occur which lasts for more than a specified time, perhaps 5ms, the switch off/recycle procedure is followed. Shut-down is accomplished by turning off all supplies simultaneously.

Such is the advance of semiconductor technology that the present sequencer, which is constructed from TTL integrated circuits hard-wired together, is now becoming obsolete. Consequently, a redesigned system making use of a micro-processor and semi-conductor memories is being developed by MSDS Ltd. This will allow much greater flexibility with regard to changes in the main programme and in the various sub-routines. In addition, its capability is such that precisely tailored switch-on voltage and power profiles for the high voltage supplies and the cathode heater supplies are to be included; those required for the cathode heaters are shown in Fig.19. The possiblity of incorporating an automatic check-out programme is also being considered. In these and other examples, the main advantage of this new concept is that alterations can be confined to the software alone, thereby reducing cost and increasing versatility.

1.3.4 Thruster control during steady-state operation

Three control loops are employed with the T4A thruster, two for the discharge chamber and one for the neutraliser. This scheme provides superior versatility to that having only a single discharge chamber loop[5,45]. In particular, it enables I_B, and thus the thrust, to be held constant, whilst separately holding η_m at its chosen high value by keeping the primary electron energy in the discharge chamber at its optimum. The latter is accomplished by maintaining constant the difference ΔV between the anode and keeper potentials. A major advantage of this dual flow control technique, apart from general versatility, is that it is possible to allow automatically for cathode degradation, without losing utilisation efficiency. As the cathode degrades, the coupling plasma potential required to obtain a given electron emission rises[35]. With a single flow control loop, ΔV might fall, because the necessary increase of anode voltage V_A could probably be gained only by decreasing the cathode flow rate, and this would conflict with the requirement of maintaining I_B constant. However, with a dual system, ΔV can be increased by adjusting the cathode flow, I_B being separately controlled via the main flow. The performance of this system is enhanced by using ΔV rather than just V_A, as in other Kaufman thrusters.

The pcu therefore incorporates circuitry for three control loops. In each loop, the parameter to be maintained constant is accurately sensed and compared with a reference. The derived error signal is then amplified and used to alter the power supplied to the heater of the appropriate vaporiser, in such a sense as to decrease the error. As an example, if the beam current rises above its set value, the error signal causes the power supplied to the main flow vaporiser heater to be reduced slightly, thereby decreasing the rate of mercury vapour flow to the discharge chamber. Cross-coupling occurs between this loop and that controlling ΔV, owing to the fact that both influence the plasma in the discharge chamber. However, the correct choice of thermal time constants[38], and the use of appropriate signal processing techniques and amplifier gains, has prevented this from becoming a significant problem.

The accuracy attained by the control loops is of considerable importance, in that it partially determines the overall operating efficiency of the thruster. This is because it is not possible to run the thruster in a routine manner at its limit of stability, where the very highest performance is achieved. Fig.20 illustrates the performance map recorded under one set of conditions; this shows

Table 2

Typical analogue telemetry outputs from T4A thruster power conditioning unit

	Parameter	Accuracy	Normal value	Operating range
1	Beam supply voltage	±2%	900V	Stabilised
2	Beam current	±2%	167mA	Loop controlled
3	Magnet current	±2%	0.30A	Stabilised
4	Anode potential	±1%	40V	Loop controlled
5	Anode current	±2%	1.167A	Stabilised
6	Main discharge keeper potential (starting	±10%	600V	Fixed
	Main discharge keeper potential (operating)	±1%	13.5V	10-20V
7	Main discharge keeper current (operating)	±5%	400mA	Stabilised
8	Accel grid potential	±5%	-300V	Stabilised
9	Accel grid current	±0.1mA	0.4mA	0-1.5mA
		±0.25mA		1.5-5mA
10	Main flow vaporiser voltage (operating)	±2%	7.7V*	In control loop
11	Hollow cathode vaporiser voltage (operating)	±2%	6.6V*	In control loop
12	Neutraliser vaporiser voltage (operating)	±2%	3.9V*	In control loop
13	Hollow cathode heater current (starting)	±10%		0-3.0A (ramp)
	Hollow cathode heater current (operating)		0	
14	Neutraliser cathode heater current (starting)	±10%		0-3.0A (ramp)
	Neutraliser cathode heater current (operating)		0	
15	Neutraliser keeper potential (starting)	±10%	600V	Fixed
	Neutraliser keeper potential (operating)	±1%	24V	Loop controlled
16	Neutraliser keeper current	±5%	300mA	Stabilised
17	Neutraliser bias potential	±5%	25V**	Stabilised
18	Neutraliser bias current	±2%	167mA	Loop controlled
19	Main isolator heater current (starting)	±10%	Values depend on thermal environment of thruster and start-up time required. Probably all set to zero during operation	
20	Cathode isolator heater current (starting)	±10%		
21	Backplate heater current (starting)	±10%		
22	Backplate heater voltage (starting)	±10%		

* Values depend on thermal conditions. Higher values used for starting

** Can be reduced to any value down to 0V, that chosen depending on the mission

that, although $\eta_m \geqslant 90\%$ is available at an energy cost of below 250eV/ion, this is very close to the stability limit, where any slight increase of ΔV or change of discharge current I_D may cause instability. A margin of safety is obviously necessary, and this is determined by the control system as well as by the characteristics of the thruster. The specified control loop accuracy is ±3%, so ΔV is maintained within about ±1V at the normal operating point. The accuracy of control of I_D is of the same order, so stability margins of 5% should be fully adequate. However, until more experience of long-term testing is gained, much larger margins of 10% of I_D and ΔV have been assumed; it should be possible to reduce these eventually, with a corresponding gain in performance.

1.3.5 The telemetry system

In accordance with thinking in the UK, ESTEC has recommended that a flight test of an ion thruster system should take place well before its operational use. In order to evaluate fully the performance of the system in orbit, it is necessary to obtain as much information as possible concerning the behaviour, in time, of all important parameters. For this reason, the pcu, in its present form, incorporates 22 analogue data outputs, together with a number of TTL-compatible status outputs.

The analogue data outputs are in the range -5V to +5V and are derived directly from voltage and current measurements, in some cases via the electrically isolating signal transfer circuits discussed in section 1.3.2. The accuracies at the nominal working points are given in Table 2 and the status outputs in Table 3.

Table 3

Telemetry status outputs

1	Position in start sequence
2	Position in re-start sequence
3	Thruster in steady-state operation
4	Beam modules on/off (three outputs)
5	Pcu input supply voltages (four outputs)

There are a number of other parameters which are important in laboratory tests, and which would be highly desirable to monitor in a flight experiment. They are not at present included in the telemetry outputs, but tentative plans are being formulated to incorporate a number of them in the system to be designed for the

1980 Ariane test flight. In particular, the measurement of several temperatures to check the thermal balance of the thruster and of its installation in the spacecraft are required, as is an indication of the overall consumption of propellant and of the flow rates through individual vaporisers. Details of these other parameters are given in Table 4.

It should be noted that all the parameters given above refer specifically to the T4A thruster operating at 10mN thrust and an exhaust velocity of 30km/s. Any change in the operating regime will alter the values given, and there are certain minor differences between the T4A and T5 devices, mainly due to improvements in the thermal design. In addition, if throttling or thrust vectoring are required, the list will need to be extended, and more command channels will also be required.

Table 4

Important parameters not included in present pcu telemetry

	Parameter	Accuracy	Normal value	Range
1	Hollow cathode flow rate (starting)	±5%	Ramp increase	<0.2mg/s
	Hollow cathode flow rate (operating)	±1%	Loop controlled 0.16mg/s	0.13-0.18mg/s
2	Main vaporiser flow rate (starting)	±5%	Fixed power	0.2-0.3mg/s
	Main vaporiser flow rate (operating)	±1%	Loop controlled 0.24mg/s	0.2-0.3mg/s
3	Neutraliser flow rate (starting)	±5%	Ramp increase	<0.3mg/s
	Neutraliser flow rate (operating)	±0.002mg/s	Loop controlled 0.008mg/s	0.006-0.015mg/s
4	Backplate temperature	±5°C	110°C-190°C*	-30°C to 190°C*
5	Hollow cathode vaporiser temperature	±0.5°C	Loop controlled	-30°C to 350°C*
6	Main flow vaporiser temperature	±0.5°C	Loop controlled	-30°C to 350°C*
7	Neutraliser vaporiser temperature	±0.5°C	Loop controlled	-30°C to 350°C*
8	Other temperatures, as required (e.g. isolator flanges, front pole, etc.)	±5°C		-30°C to 400°C*
9	Bellows tank pressure	±5%	Blow down type	1-2bar
10	Bellows tank temperature	±5°C	Satellite temp.	
11	Position of bellows in tank	±10%		0-3.6cm (5kg capacity)

* Depends on thruster installation, environment and earth screen open area ratio

As regards operational flight, it will probably not be necessary to continuously supply to ground stations all the data described above. It is envisaged that only a single command to start thrusting will normally be required, with a second command to terminate each operational period. All other actions concerning each individual thruster are assumed to be carried out automatically, under control of the sequencer built into the pcu supplying that thruster. In addition, it is possible that a master sequencer, or an on-board computer[44], will automatically switch redundant thrusters and pcus to make allowance for any failures that have occurred. Only exceptionally should intervention by ground control be necessary. However, in the event of a failure, diagnosis of the cause will only be possible if adequate information can be transmitted to the ground, so the flight version of the pcu should also include a comprehensive system of telemetry channels for use where necessary. The design of such a system must, of course, be properly integrated into the overall spacecraft communications package, and it may not, therefore, be possible to achieve all the desired aims.

1.4 The propellant feed system

It is envisaged that an electric propulsion system in a communications satellite is likely to require two or more separate propellant tanks, which will be interconnected for redundancy purposes and will enable CG shifts to be minimised as propellant is consumed. This scheme assumes that mercury thrusters are employed, because it requires the use of reliable electrical isolators, which are not available if cesium propellant is selected. Without these isolators, each thruster has to be supplied from its own tankage system, which must contain sufficient propellant for all eventualities. As any redundant thrusters must be similarly supplied, the interconnected 'ring-main' scheme, employing electrical isolators, is obviously by far the lightest alternative; with it, the total propellant load carried by the spacecraft need be no greater than that required to supply the total impulse specified for the mission in question.

The propellant feed system planned for a UK ion thruster installation therefore consists of two or more tanks, interconnected by narrow bore stainless steel tubing, with appropriate demountable unions and valves at the tanks and at the thrusters. The whole system will be at spacecraft potential, and should cause no integration problems. Temperature control will not be at all critical, owing to the convenient melting and boiling points of mercury, which are $-38.9^{o}C$ and $356.7^{o}C$ respectively at 1 bar pressure.

1.4.1 The propellant tank

Estimates of probable mission requirements indicate that the total propellant needed for a typical mission might be about 10kg. Accordingly, a tank of 5kg capacity (Fig.21) has been designed and built, and is at present being tested. This design is based on an earlier experimental 3kg capacity tank[46], shown in Fig.2, which was intended for use in a satellite launched by Black Arrow. It will be seen in Fig.21 that a metallic bellows is used to separate the mercury from the nitrogen pressurising gas, which is also contained within the tank shell. The system operates in a 'blow down' mode over a pressure range of 2-1 bar and with an estimated expulsion efficiency of 95% and a weight of under 0.5kg. It will be appreciated that, because of the bellows technique employed, it is comparatively easy to produce a tank of different capacity, if desired, merely by altering the length of the bellows and of the tank.

The decision to use a bellows design followed an experimental comparison[46] of that concept with another commonly adopted alternative, a spherical tank in which the pressurising gas and propellant are separated by a neoprene diaphragm. Although both performed well in filling and expulsion tests, the greater potential reliability of the bellows arrangement caused it to be adopted for further development. The main area in which it was considered to be superior was that of gas permeation into the propellant. With a properly tested stainless steel bellows this should be negligible over a period of many years, whereas no such guarantee can be given for elastomeric membranes.

1.4.2 Propellant stop valves

It is envisaged that it will be necessary to position a latching stop valve at the exit from each tank and at the input to each thruster. These are required to prevent the build-up of unacceptable hydrostatic pressures in the pipe-lines during the acceleration and vibration to be expected in the launch phase of any mission. Such pressures could rupture the porous tungsten plugs in the vaporisers or, at least, cause them to leak liquid mercury; these plugs can withstand pressures of up to about 6 bar. Damage might also be caused to the tank bellows.

As considerable valve development expertise exists in the UK, practical work has only recently been commenced, although a number of preliminary designs have been considered. These designs follow two distinct paths. One is conventional, using modified versions of existing UK valves intended for other

purposes; the weight of these would be 80-100g each, and their development should not present much difficulty. The other approach involves an attempt to integrate a thermally-actuated valve with each vaporiser. This is a more formidable task, because such valves would be thermally cycled throughout a mission, must withstand contact with hot mercury, yet must be very small so that they radiate little energy. A choice between these concepts will be made during the development programme described in section 3.

1.4.3 Pipelines and connectors

Unlike cesium, mercury is a very easy propellant to manage and to distribute around a spacecraft. The availability of electrical isolators allows the pipelines to be at spacecraft potential, and the reasonably low melting point of mercury eliminates the need to use heated components. In fact, the proposed system is very simple, consisting of a ring-main of 1.5mm outside diameter stainless steel pipe connecting all tanks and thrusters, with valves positioned according to the requirements of the mission and the overall spacecraft design.

It is considered that demountable connec ors should be used to join the pipeline to valves, tanks and thrusters. This offers maximum convenience of installation and testing, while not significantly reducing system reliability. Two types of connector have been tested so far. One is of the all-metal 'swagelock' variety, while the other employs a simple rubber 'O'-ring and a 45° sealing chamfer on one of the mating surfaces (Fig.22). Both have proved satisfactory over many thousands of hours of use, although the 'O'-ring type appears generally superior.

1.5 Performance of the T4A thruster

In all respects, the performance of the T4A thruster has met or exceeded the original UK Specification, and must rank amongst the best available. In particular, it should be pointed out that it simultaneously achieves an extremely high efficiency, a very flat plasma density profile and excellent stability, while providing minimal adverse thruster/spacecraft interactions. As regards these interactions, the small beam divergence is most beneficial, being better than quoted for many other thrusters[5,6], and the rate of deposition of sputtered grid material on surrounding surfaces has been shown to be acceptable for most applications (section 2.2.1).

In the following discussion of performance, emphasis will be laid on measurements made during the two 1000 hour life-tests so far performed on a T4A

thruster, but other results will also be referred to where appropriate. These life-tests were carried out at the Fulmer Research Institute on the same basic thruster, but with various changes being made for the second test to investigate the long-term performance of an improved set of critical components. However, before commencing the discussion of the performance of the thruster, the symbols and parameters used must be defined; this is done in the following section.

1.5.1 Definitions of symbols and parameters used

In common with most branches of science and engineering, there is, at times, some confusion about the exact meanings of the parameters used to describe the performance of an ion thruster system. As an example, the energy cost per beam ion can be calculated from the discharge power used directly for ionisation, the total discharge power, or the total power fed to the discharge chamber in any form. In addition, corrections may be applied to account for doubly-charged ions. It is therefore evident that several different values can be produced for what is essentially the same parameter, so a careful definition is vital, especially if comparisons are being made between different systems.

The symbols used in these definitions and elsewhere in this document are defined below.

Symbols

D	fraction of beam current due to doubly-charged ions (see definition (v))
e	charge on an electron
F	thrust (see (b))
F^1	thrust corrected for presence of doubly-charged ions (see (v))
f	ion extraction efficiency (see (f))
g_0	acceleration due to gravity at sea level
I_A	anode current ($= I_D + I_B$)
I_B	total beam current
I_B^{++}	the contribution to the beam current from doubly-charged ions (see (v))
I_D	discharge current
I_s^+	total ion current diffusing to the plane of the screen grid
I_{sc}^+	ion current collected by, or impinging on, the screen grid
I_{sp}	specific impulse (see (i))
I_T^+	total rate of ion production in the discharge chamber

I_m	solenoid current
$\dot{m}$	propellant mass flow rate
m_i	mass of a propellant ion
$\dot{m}_N$	propellant mass flow rate supplied to the neutraliser
$\dot{m}_T$	propellant mass flow rate supplied to the discharge chamber (see (c))
P_D	power input to the discharge chamber used in the ionisation process
P_T	total power supplied to the thruster
V_A	anode potential
V_T	net accelerating voltage through which beam ions fall
V_{ac}	accel grid potential
v_e	exhaust velocity (see (a))
V_k	discharge chamber keeper voltage
ΔV	($= V_A - V_k$) energy of primary electrons
ε	discharge chamber efficiency (see (e))
η_d	beam divergence efficiency (see (w))
η_e	total thruster electrical efficiency (see (g))
η_m	propellant utilisation efficiency (see (d))
η_{mT}	propellant utilisation efficiency, including neutraliser (see (d))
η_T	total thruster efficiency (see (g))
ϕ	semi-angle of beam divergence
τ	grid geometrical transparency (see (q))
τ_e	effective screen grid transparency (see (r))

The parameters defined below do not constitute an exhaustive list, but are adequate for describing most aspects of the physical characteristics and performance of a Kaufman-type electron bombardment thruster. In particular, they indicate the methods of applying the various corrections that are so often omitted from published data.

(a) Exhaust velocity

Calculated directly from the set voltage V_T through which the beam ions fall, according to:

$$v_e = (2eV_T/m_i)^{\frac{1}{2}} \quad .$$

If doubly-charged ions are present in the beam, their velocity will be:

$$v_e^{++} = (4eV_T/m_i)^{\frac{1}{2}} \quad .$$

(b) Thrust

Calculated directly from electrical parameters, according to:

$$F = I_B(2V_T m_i/e)^{\frac{1}{2}} = I_B m_i v_e/e \quad .$$

Corrections are required if the beam contains doubly-charged ions (see (v)) or if the beam divergence is large (see (w)).

(c) Propellant flow rate

This parameter, $\dot{m}_T$, is normally defined as the mass of propellant delivered to the discharge chamber in unit time. To assess the overall performance of the thruster, the mass flow rate to any neutraliser, $\dot{m}_N$, must be added to $\dot{m}_T$.

(d) Propellant utilisation efficiency

The value normally quoted, η_m , is defined as that fraction of the propellant entering the discharge chamber of the thruster which is usefully accelerated into the beam, thus contributing to the thrust. Thus

$$\eta_m = \frac{I_B m_i}{e\dot{m}_T} \quad .$$

The overall mass utilisation efficiency must include the neutraliser system, so

$$\eta_{mT} = \frac{I_B m_i}{e(\dot{m}_T + \dot{m}_N)} \quad .$$

Corrections are required if the beam contains doubly-charged ions (see (v)).

(e) Discharge chamber efficiency

This is defined as the mean discharge energy ε required to produce one beam ion. Its units are conventionally eV/ion. Thus

$$\varepsilon = P_D/I_B \quad \text{eV/ion}$$

where $P_D = I_D V_A$ for the Kaufman thruster (note that $I_D = I_A - I_B$ and that keeper discharge power is not included).

(f) Ion extraction efficiency

This parameter gives an indication of how effectively the ions produced in the discharge chamber are used in providing a beam. It is defined as the ratio of the beam current to the total ion production rate, thus

$$f = I_B/I_T^+ \ .$$

Note that it depends on the diffusion rate of ions to the grid system and on the efficiency of extraction through the grid apertures.

(g) Total thruster electrical efficiency

This is defined as the fraction of the total power supplied to the thruster, P_T, which is usefully employed in accelerating beam ions. Thus

$$\eta_e = m_i v_e^2 I_B / 2eP_T = Fv_e/2P_T \ .$$

Here P_T includes all power supplied to the discharge chamber, magnets, heaters, vaporisers, grids, beam, neutraliser, etc., during steady state operation. Corrections are required if the beam contains doubly-charged ions (see (v)) or if beam divergence is large (see (w)).

(h) Total thruster efficiency

This is defined as the product of the total electrical and overall utilisation efficiencies, i.e.

$$\eta_T = \eta_{mT}\eta_e \ .$$

(i) Specific impulse

This is defined as the ratio of the thrust to the total rate of use of propellant in units of sea-level weight, thus

$$I_{sp} = \frac{\eta_m \dot{m}_T v_e}{(\dot{m}_T + \dot{m}_N) g_0} = \frac{\eta_{mT} v_e}{g_0} \ .$$

Corrections should be applied if the beam contains doubly-charged ions (see (v)) or if there is strong beam divergence (see (w)).

(j) Thruster diameter

This is defined as the diameter of the circle enclosing all ion extraction holes in the grid system.

(k) Thruster geometric axis

A line perpendicular to the plane of the edge of the outermost grid (the accel grid in a two-grid system, or the decel grid in a triple-grid sytem), passing through the centre of the circle defined in (j) above.

(l) Beam divergence, ϕ

This is defined in this report as the semi-angle of a cone whose surface is formed from the straight ion stream tubes, far from the thruster, bounding 95% of the ion beam current. It should be emphasised that measurements of this parameter should be made sufficiently far from the grids to ensure that the ion stream tubes are straight.

From the point of view of spacecraft integration, this definition is more appropriate than the conventional alternative, which is to take, at an arbitrary distance from the grids, the semi-angle of the truncated cone containing 95% of the beam ions. The diameter of the truncated end is usually defined as in (j) and is situated in the exit plane of the grid system.

Reference to Fig.10a will show that this latter definition can give a misleading, over-optimistic value. If the arbitrary distance from the grids is taken as 40cm, this conventional definition gives a value (which is more easily measured) of divergence of only 8°, whereas the stream tube definition gives $\phi = 17^{\circ}$. The two values approach each other, however, in cases where curved stream tubes are not produced.

(m) Plasma and beam density profiles

These may be characterised by reference to the diameter at which the measured density has fallen to one half of its peak value.

(n) Thrust axis

This is defined as the line along which the total thrust produced by the thruster acts. It may be determined by use of a thrust balance, or by integration of ion probe maps of ion density distributions at several distances from the thruster. If the latter technique is employed, corrections must be applied to allow for the radial components of the ion velocities, or directional probes must be utilised.

(o) Thrust axis misalignment

This is defined as the angle between the geometric axis (k) and the thrust axis (n).

(p) Thrust axis displacement

This is defined as the distance between centre of the circle defined in (j) and the point at which the thrust axis cuts the exit plane of the grid system, as defined in (k).

(q) Grid geometrical transparency, τ

This is the ratio of the area of the holes in any part of the grid in question to the total area of that part.

(r) Effective screen grid transparency

This parameter determines the actual ion current extraction capability of a grid system. It can be greater than the geometrical transparency of the screen grid, owing to the curvature of the plasma sheath at each aperture. It is defined as the ratio of the extracted beam current to the total ion current diffusing to the plane of the screen grid, i.e.

$$\tau_e = I_B / I_s^+ = I_B / \left(I_{sc}^+ + I_B \right) = f I_T^+ / I_s^+ \; .$$

(s) Grid compensation

This term refers to the alteration of the positions of the holes in a grid (normally the accel grid) to change the divergence of the ion beam by electrostatic deflection of individual beamlets. The degree of compensation is defined by the ratio of the displacement of the holes to their original separation (i.e. to the separation of the centres of the equivalent holes in the other grid).

(t) Thruster mass

This is the mass of all components carried by the mounting points provided in a satellite for a thruster. It thus includes all the structure of the thruster, the neutraliser, the earth screen, any integral mounting structure such as special high voltage insulators, and any integral wiring, plugs and sockets, and propellant pipework. It should exclude the masses of propellant control valves, unless integral with other included components, and any gimballing system; the masses of these items should be separately given.

(u) Neutraliser coupling potential

This is defined as the potential between the electron-emitting neutraliser surface (the tip of the hollow cathode, or the centre point of a hot wire) and

the thruster electrical earth. The electrical earth would normally be the negative terminal of the beam power supply; in most circumstances, it would be satellite potential. (Note that the coupling potential, defined in this way, is not usually the actual potential responsible for transporting neutraliser electrons into the beam, because the centre of the beam is unlikely to be exactly at thruster earth potential and the potential of the neutraliser plasma will not equal neutraliser cathode potential.)

(v) Correction for doubly-charged ions

If these constitute a fraction D of the beam current, D is defined as

$$D = I_B^{++} / I_B \quad .$$

Their presence alters the thrust, propellant utilisation efficiency, thruster electrical efficiency, specific impulse, and other derived parameters. When corrections have been applied to account for the doubly-charged ions, this should be stated in presenting the results. If it is not explicitly stated, it will normally be assumed that no corrections have been included.

As an example of the corrections to be applied, the thrust is reduced from that given by the expression in (b) to

$$F^1 = I_B \left(\frac{2m_i V_T}{e}\right)^{\frac{1}{2}} \left[1 - D\left(1 - \frac{1}{\sqrt{2}}\right)\right]$$

$$= F(1 - 0.29D) \quad .$$

(w) Correction for beam divergence

This depends on the divergence efficiency of the beam, which is defined as

$$\eta_d = \frac{\text{momentum directed along thrust axis}}{\text{total momentum in the beam}} \quad .$$

It can be evaluated numerically only if full information is available concerning the density profile and divergence of the beam. In essence, it is necessary to know the trajectories of all ions.

When corrections have been applied to account for this effect, this should be stated in presenting the data. If it is not explicitly stated, it will normally be assumed that no correction has been applied.

1.5.2 Electrical and mass utilisation efficiencies under steady-state conditions

In common with most other thrusters, the overall performance of the discharge chamber and ion extraction system may be illustrated by reference to maps of the mean energy cost ε of producing a beam ion as a function of mass utilisation efficiency η_m. The example shown in Fig.20 was obtained at the end of a 1000 hour life-test using a 0.5% compensated grid set. The other parameters employed in this presentation are discharge current I_D and ΔV; the latter is a particularly significant quantity, as it is close to the primary electron energy[9].

Although the values shown are not compensated for the presence of doubly-charged ions, for the keeper discharge power, or for the neutraliser mass throughput, the performance can still be seen to be excellent, with η_m exceeding 90% for ε above 200eV/ion.

If the above-mentioned corrections to these values are made, η_m should be reduced by about 2 to 3% to account for the neutraliser flow rate of 0.008 to 0.012mg/s and by about 3% to allow for the presence of doubly-charged ions (section 1.5.4). Similarly, the doubly-charged ions increase the apparent value of ε by about 3.5%, and the keeper discharge power of about 6.9W further increases it by another 18%. As an example of the resulting numerical values, the effect of these corrections on the mean performance of the thruster throughout its second 1000 hour life-test is presented in Table 5.

Table 5

Values of η_m, ε and F, with various corrections

	η_m (%)	ε (eV/ion)	Thrust (mN)
Uncorrected values	89.5	237	10.5
Corrected for Hg^{++}	86.5	245	10.3
Corrected for Hg^{++} and keeper power	86.5	287	10.3
Corrected for Hg^{++}, keeper power and neutraliser	83.5 to 84.5	287	10.3

The power inputs to the various thruster components under steady-state life-test conditions were as follows:

Discharge	39.7W	Accel grid	1.7W
Keeper discharge	6.9W	Beam	157.8W
Field coils	3.4W	Neutraliser vaporiser	1.5W
Main flow vaporiser	2.5W	Neutraliser keeper	7.2W
Cathode vaporiser	2.5W	Neutraliser bias	0
		Heaters	0

The power supplied to all heaters is zero because adequate thermal energy is fed back to the feed system components from the discharge chamber and cathodes to prevent mercury vapour condensation, and both neutraliser and main cathodes operate solely on ion bombardment heating. The heaters are used only during start-up. Although a neutraliser bias supply is provided in the pcu, it is not necessary for thruster operation; it could be employed in orbit, however, to actively bias the spacecraft to any required potential relative to space[32].

The total P_T of the powers given above is 223.2W, giving an overall power to thrust ratio of 21.7W/mN at 10.3mN thrust and a total electrical efficiency η_e of 70.7%. When multiplied by η_m to give the overall thruster efficiency η_T, this is found to be 63.3% using the uncorrected value of η_m and 59.4% after applying the above corrections. It should be noted that these efficiencies can be increased very easily by operating at a higher exhaust velocity.

This excellent performance is not restricted to the thrust level of the life-test. Successful operation over a wide range of thrust levels between 6.5 and 17mN has been achieved, although life-testing has been carried out only at 10mN. This impressive versatility is due to the sound design of the thruster, and to the close control of its performance given by the dual propellant flow system and the variable magnetic field. A wide-range of throttling capability could therefore be provided if desired, but at the cost of added pcu complexity. It has also been found that the performance can be improved further by using a screen grid of higher open area ratio. However, mechanical considerations dictate that round holes cannot then be employed, so a technique for manufacturing hexagonal holes by spark erosion has been developed[39], giving values of τ up to 90%. Several grid sets of this sort have accumulated many hundreds of hours of operation without failure, although it has been found that holes on the periphery of the accel grid suffer some direct ion impingement damage, especially at the beginning of a long-duration test (section 2.2.1).

It has also been widely reported that the utilisation efficiency of a Kaufman thruster can be increased by a very large amount by using an accel grid

having a very low open area ratio[5,48]. This is claimed to minimise the loss of neutral propellant, thereby enhancing the effective ionisation efficiency. However, in the experiments reported to date, the holes have been made by ion machining on the thruster in question[48], and this results in a number of serious disadvantages. Possibly the most important in the short term is the production of large quantities of sputtered material during the machining process, which requires hundreds of hours to complete. In the longer term, because the accel grid holes form where the embryonic ion beamlets dictate, no control is possible of the directions of the beamlets, so beam divergence may tend to be unacceptably large. A third problem arises if the grids are disturbed in any way, either by dismantling for cleaning or inspection, or by thermal or vibration testing. This disturbance will almost certainly result in a small amount of misalignment, causing renewed ion machining of the accel holes and an increase in the rate of production of sputtered material.

It should also be pointed out that the large performance improvements obtained by this technique were achieved on a thruster which was, initially, much less efficient than the T4A [5]. Very much smaller improvements would be expected when starting with a highly efficient device. In view of this and the disadvantages presented above, low priority has been allocated in the UK programme to the study of small hole accel grids, although samples have been successfully made for testing.

1.5.3 Discharge chamber plasma density profile

During development of the thruster, the discharge chamber characteristics have been extensively studied by a variety of techniques, including Langmuir probes, wall probes, and the separate measurement of the ion and electron currents to all components. There thus exists a good understanding of the phenomena occurring within the discharge chamber. As most of this work has been published[7,8,9,19], reference will be made here only to one aspect, which is of particular relevance to obtaining long thruster lifetimes.

In this context, one of the most important characteristics is the shape of the plasma density profile in the discharge chamber, because this determines the way in which the charge-exchange erosion is distributed over the outer face of the accel grid. A strongly peaked profile is very undesirable because it causes the erosion to be concentrated over the central area of the grid, making it likely that a premature failure could occur there. The ideal profile, to minimise this possibility, is completely flat, but this is not attainable whilst also achieving high efficiency.

The density profile within the T4A thruster is shown as curve (a) in Fig.23. Its shape may be compared to those found in other thrusters by reference to the radius at which half the peak density occurs. In this case this dimension is 43mm, whereas in an earlier version of the thruster, illustrated in curve (b), the equivalent value was 30 to 32mm. As illustrated in curve (c), it is possible to achieve an even flatter distribution by modifying the thruster so that the primary electrons are launched into the discharge chamber on a larger radius. However, efficiency is then reduced, and the optimum thrust level is increased to 15mN.

1.5.4 The production of doubly-charged ions

A feature of the thruster which has already been referred to is the production of doubly-charged ions. Their contribution to the beam current was measured in the earlier diagnostic thruster from which T4A was scaled by use of a a time-of-flight mass spectrometer[8]. The results, which are shown in Fig.24, indicate that the ratio of doubly- to singly-charged ions is a steadily increasing function of V_A . There is good reason to expect that the method of scaling did not alter the rate of production by a substantial amount[8], so the data in Fig.24 can also be applied to the T4A thruster. This view is supported by preliminary experiments with a quadrupole mass spectrometer, which indicated that the threshold for production, about 29 to 30V, and the initial rate of rise of the data were close to those in Fig.24. Only at high V_A was a discrepancy observed, and this may have been due to experimental errors.

Using these data, the beam current during the second 1000 hour life-test contained a contribution of about 7%, or 11mA, due to the presence of doubly-charged ions, V_A being 39.7V. This represents a loss of about 3% in η_m and, as explained in section 1.2.8, is probably the cause of any discharge chamber sputtering that occurs.

1.5.5 Thruster stability under steady-state conditions

Another characteristic of considerable importance is that of stability. It has been established, during several thousand hours of testing in three establishments, that the T4A thruster is remarkably stable. It is virtually impossible to cause the discharge to extinguish accidentally, noise levels are very low, and inter-grid arcs which trip the beam or accel power supplies have never been observed during steady operation. As an example of the electrical noise, the peak noise voltage on the thruster body under one set of conditions has been measured at 0.6V with laboratory power supplies and 0.2V with the pcu.

The peak performance shown in Fig.20 is reached with $\Delta V \sim 31$ to 32V, just below the stability limit. At this limit, the electrical noise increases and performance falls off; the discharge does not extinguish. As mentioned in section 1.3.4, it is advisable to operate away from the limit, the 'stability margin' required being determined by factors such as the degree of power supply stabilisation available, the measurement accuracy, and the overall accuracy of the thruster control loops employed.

The pcu provides 1% measurement accuracy, 3% voltage and current stabilisation, and 3% control loop accuracy. Consequently, operation within about 3 to 5% of the stability limit as regards both ΔV and I_D should be satisfactory. However, there is interaction between most of the important thruster parameters and, in particular, between the two discharge chamber control loops[38]. It is therefore thought advisable at present to operate with a stability margin of about 10%, reducing ΔV at the operating point to 28 to 29V and increasing I_D from about 0.9 to 1.0A.

These values were chosen for the 1000 hour life-tests, and completely satisfactory results were obtained, despite the thruster being under manual control. There is thus evidence that a 10% stability margin is entirely adequate, especially using active control loops.

1.5.6 The beam and neutraliser

The characteristics of the ion beam have already been discussed in connection with the choice of grid systems, current density profiles for three related grid systems being shown in Fig.10. In all cases, including the use of grids with hexagonal holes, satisfactory performance has been achieved, with particularly low beam divergences with accel grid compensations of 0.5 and 1.0%. As already mentioned, with this thruster there seems to be little advantage to be gained from using very small accel grid open area ratios.

Although both 0.5% and 1% compensated grids have been successfully tested for 1000 hours, and the sputtering rate of each is acceptably small, the former have been chosen for future work. This is to avoid the slight additional erosion which occurs through direct ion impingement in the peripheral holes of a 1% compensated accel grid in the first few hours of operation. In addition, the 0.5% compensated grids have been run for a much longer period with a hollow cathode neutraliser; during a 1000 hour life-test, this combination proved entirely satisfactory, with accel grid erosion due to charge-exchange being no more severe than with a hot-wire neutraliser.

It had earlier been shown in diode tests[33] that under some circumstances hollow cathode neutralisers can be operated at tip temperatures several hundred degrees lower than has been hitherto common practice and at flow rates well below 0.01mg/s. Their characteristics are then controlled by the keeper discharge. It has been confirmed that this type of performance can be achieved in thruster operation. In particular, no cathode heater power is necessary and very low flow rates (typically 0.01mg/s) may be employed. This is illustrated by the data shown in Fig.25, which were taken just before a 1000 hour life-test.

A further result of these neutralisation studies, again evident from Fig.25, is that no bias supply is necessary; the life-test referred to was run in this mode, with complete neutralisation being guaranteed by electrically floating the thruster and its power supply system. As the thruster system could be operated in this mode in a spacecraft, with the ion beam coupling to space potential, a test under these conditions is realistic. The bias supply provided in the pcu can be used if it is necessary to adjust the spacecraft potential relative to space plasma potential.

1.5.7 The starting sequence

In north-south station-keeping missions, the start-up of the thruster system can have an important influence on the overall electrical and utilisation efficiencies, especially if the time for which full thrust is produced is relatively short. The aim should be to minimise the amount of energy and propellant used during the start sequence. This is probably best accomplished by employing a rapid sequence, although care must be taken to avoid damaging heaters and other components through repetitive thermal shocks. Consequently, one aim of the T4A development programme has been to attain a start-up time of less than 15 minutes with an energy consumption of below 25W h. Both these objectives have been surpassed by large margins, and thermal cycling of various components has demonstrated that they should be capable of withstanding such starts for many thousands of cycles. It should be mentioned that, with battery operation of a thruster system, the energy consumption is a more important parameter than the time; for this reason, an earlier 5 minute start-up requirement was relaxed, although thermal cycling tests have confirmed that the critical components are sufficiently robust to withstand the treatment they would receive if such starts were mandatory.

Up to the present, most of the starting tests have been performed manually, although the faster times are more easily recorded using the sequencer built

into the pcu. Commencing from room temperature, the time needed for the latest start sequence studied is 12 minutes and the energy required is about 12W h; the latter can probably be reduced by starting the discharge at a lower backplate temperature. The power and neutral propellant flow variation during this sequence are shown in Fig.26; depending on the speed of the sequence, the propellant used is about 50 to 70mg.

A simplified version of the more complex sequence currently employed by the pcu is shown in Fig.18. However, during further planned development of the thruster and pcu, adjustments may be made to various time delays, voltage and current reference levels and to the details of the correction sub-routines; such changes may also be necessary in the interests of compatibility of the complete thruster system with a particular spacecraft or mission.

Using this pcu sequence, the time taken to start is largely determined by the power levels fed to the isolator and backplate heaters, although the speed of response of the cathode and vaporiser heaters is also important. All heaters are much more highly rated than necessary for a normal start, so extremely rapid heating is possible if necessary. For example, the cathode vaporiser normally runs at about 2.5W, yet it has been extensively tested at 15W, without any failures. Although discharge initiation to a cathode is dependent on random phenomena[10], the power level normally required in the cathode heater increases with time as the sequence proceeds, but is of the order of 14 to 20W (Fig.19) at the start. The heater is rated for well above 20W operation, many thousands of thermal cycles having been accomplished at about 35W, so the safety margin is considerable.

In general, the main cathode discharge starts near its normal operating flow rate, while the neutraliser cathode, being exposed directly to vacuum, needs more propellant than the main cathode. Consequently, during starting, the neutraliser vaporiser is much hotter than in steady operation and its rate of heat loss determines the time taken for the neutraliser system to attain its correct characteristics following the establishment of the discharge. In reaching its proper regime, the discharge may pass from the 'spot' mode, through the 'plume' mode, into the 'diffusion' mode[33], and the output characteristics of its keeper power supply are selected to ensure that this is possible. The main flow rate can be at a very low level when the discharge is started, but its rate of rise is chosen so that it is close to its correct operating value as the beam is turned on.

If either the main or neutraliser discharges fail to ignite within a specified time the pcu is designed to initiate a correction sub-routine. This basically increases the flow rate, which has been shown[10] to improve the starting characteristics of a cathode. At the same time, the cathode temperature usually continues to increase, due to its thermal time constant, which further improves the chances of obtaining a discharge. If the main keeper discharge is satisfactory, but transfer to the anode does not occur, a separate correction sub-routine can be used; this problem has not so far occurred.

Once the two discharges have been established, the respective flow rates are adjusted towards their normal settings, thus preparing the way for the closure of the discharge control loop.

After application of thruster and accel grid potentials, the arcing condition is sensed by comparing beam and accel grid currents with preset limits. The arc recycle procedure is very rapid, occupying 1 to 2 seconds, so it is not necessary to consider the effect on the vaporisers, because they have far longer thermal time constants.

1.5.8 The shut-down procedure

Shut-down of the thruster system is accomplished by turning off all power supplies simultaneously, which requires the minimum of circuitry. However, while the vaporisers are cooling, they are exhausting mercury vapour into the thruster, and this waste must be considered in evaluating overall performance. This loss is about 50mg, giving a total loss during start-up and shut-down of about 120mg, for the 12 minutes start sequence.

After the discharge has been extinguished, the thruster cools at a rate determined by its environment and the methods available for it to lose heat. As its design minimises conduction to the satellite, radiation must dominate, with the earth screen largely influencing this aspect of performance. As shown in Fig.27, a high open area ratio gives a more rapid heat loss than an opaque screen.

1.5.9 Control characteristics

The control concepts discussed in section 1.3.4 have been shown experimentally[38] to be satisfactory, although they have not yet been evaluated during a long life-test. The accuracy of response of these loops to extremely severe transient conditions has been determined, with excellent results. An example is shown in Fig.28, for the case of a complete interruption for 30 seconds of

the power supplied to the main flow vaporiser. It will be seen that the maximum error in I_B was below 2%; this is partly due to the thermal time constant of the main flow system, and partly due to the cross-coupling between the control loops, which caused the hollow cathode flow rate to increase to compensate for the change in ΔV following the fall in main flow rate.

It was at one time expected that this interaction between the two discharge chamber control loops might cause instability. However, it was found that closing both loops simultaneously does not degrade the stability of the system in any way, and no special measures are needed to achieve satisfactory control[38]. This excellent response is attributed to the thermal design of the feed system, which provides a time constant of about 3 minutes for the main flow vaporiser, but about 20 seconds for the hollow cathode vaporiser.

The neutraliser control loop is relatively simple, the flow rate being regulated to maintain the keeper potential constant. The keeper current is separately controlled by the power supply, without reference to external signals. This concept has been tested and has been proved satisfactory, although long-term tests remain to be carried out. Cathode degradation is allowed for automatically by increasing the flow rate.

1.5.10 Thrust and thrust vector characteristics

The design thrust F of 10mN is maintained constant by the control system during steady-state operation. This is accomplished by controlling the beam current, at constant beam voltage V_T. At the same time, η_m is maintained constant by controlling ΔV. The maximum error in the thrust level is determined by the accuracy with which the pcu defines I_B and V_T (section 1.5.1). These are specified as ±3% and ±5% respectively for the breadboard pcu, giving a calculated possible error in F of ±4%. Any such variation can be deduced immediately, during operation, from readings of the appropriate electrical parameters.

There is good reason from the SERT II flight[21] to correlate values of F derived electrically with the thrust actually produced in space. However, some provision for a check with a thrust balance has been made, an instrument having been constructed by the RAE for this purpose.

The balance consists of a platform floating in mercury, with very weak restraining forces being supplied by carefully designed springs. In this way, high sensitivity to impressed forces is achieved. The thruster is mounted on

this platform, with power supplies being taken to it via mercury-pool contacts. A null deflection technique is employed for recording the thrust, an electromagnetic force feedback system being used, together with inductive position sensors. The whole balance is carried by specially designed anti-vibration mountings, which incorporate a remote levelling facility.

It should be pointed out that no thrust is produced during the start-up sequence, until the beam and accel grid supplies are turned on. The latter switch-on process occupies milliseconds only, so unacceptable thrust transients will not result from it. Immediately after the beam is first emitted, F may not be at its correct value, because the control loops require time to function. However, V_T will be correct from the beginning of thrusting and, as indicated in Fig.28, the maximum time taken for I_B to stabilise at its specified value is of the order of 3 minutes. The initial thrust variation will therefore occupy a similar time. In any case, the total change in F is unlikely to be very great, because both main and hollow cathode flow rates are designed to be approximately correct at their steady-state values at this stage of the starting sequence.

There is an even less pronounced transient at shut-down, due to the fact that the high voltage supplies are switched off in a time of milliseconds, starting from the steady-state thrusting condition.

At the present, there is no evidence to suggest that the thrust vector deviates appreciably from the geometrical axis of the thruster, or that its direction varies with time. Apart from the neutraliser, the thruster is completely symmetric about its axis, and extensive probing both within the discharge chamber and in the beam has not revealed any indication of a cause of significant non-axial thrust. There is also no reason to believe that asymmetry occurs during start-up and as the thruster approaches steady-state conditions.

If any deviations from the geometrical axis do occur, either of a transient nature or during steady-state operation, they are more likely to be caused by the grid system, in particular by a systematic misalignment of the pairs of holes in the screen and accel grids[30]. Such misalignments produce electrostatic vectoring, which can exceed 10° in extreme cases[49]. For this reason, great care is taken in setting up the grid system, and it is designed to accommodate radial thermal expansion of its separate parts without misalignment[18]. Despite this care in design and in setting up, there has been, on rare occasions, an indication that some misalignment has been caused by extensive thermal cycling, so an improved grid mounting system has been devised for the T5 thruster (section 1.6).

A review of the evidence available to date suggests that thrust vector misalignment is unlikely to prove to be a problem with a properly designed grid system. However, caution dictates that a significant value for this parameter be assumed in calculations of the performance of an ion thruster system; $\pm 3^{o}$ has been chosen for the T4A device[50].

1.5.11 Throttling

For certain thruster mounting configurations, the ability to throttle the thrust, either in discrete steps or continuously, may be a useful characteristic. For example, it may be necessary to mount individual thrusters so that their thrust vectors do not pass anywhere near the CG of the spacecraft. In that case, some method of balancing the torques applies about the CG would be most useful, and throttling could be employed.

It has been established that the T4A design is capable of being throttled continuously from 7 to 15mN, without mechanical change or appreciable loss of performance, and at least 17mN is obtainable. This is done simply by changing the flow rate produced by the main flow vaporiser to alter I_B as desired. At the same time, ΔV is kept constant to maintain ionisation efficiency, while I_D and the solenoid current I_m are varied to give the appropriate current of energetic primary electrons. These parameters are shown as a function of thrust in Fig.29.

This wide range of thrust is easily available in the laboratory or in flight, the required value being selected merely by altering the reference voltages applied to the beam current control loop, the solenoid current supply and the discharge current stabilisation circuit. It may also be necessary to alter the neutraliser control loop in a similar way if a large increase of I_B is to be demanded.

It should be pointed out that the need to use high values of F, even only occasionally, will require that the power capability of a number of pcu modules be increased significantly, raising the pcu mass. This is particularly true of the beam and discharge supplies. There is, consequently, a mass penalty to the implementation of a policy of employing throttling, but it is unlikely to be serious. In fact, it should be negligible for small excursions of F, say $\pm 10\%$. However, it should be emphasised that, at present, all life-testing of the thruster has been carried out at 10mN only.

1.5.12 Thrust vectoring

Thrust vectoring, using the scheme provisionally devised for the UK thruster, is different to throttling in that it does not require any changes to the pcu or to the thruster operating conditions. Although there are many possible methods of vectoring[49], including electrostatic techniques, grid translation and manipulation of the plasma density profile, they all involve major changes to the thruster and, probably, reductions in overall efficiency and reliability. It was therefore decided to leave the thruster unaltered and to employ a gimballing system, should vectoring prove necessary.

Preliminary design work has been carried out as part of the UK programme, and it appears that a very simple system can be employed, which, nevertheless, has the potential of providing high accuracy, reproducibility and durability. In principle, flexural mountings are proposed to avoid problems associated with long-life bearings, and stepper motors provide the high-accuracy drive and position monitoring.

As regards the need for vectoring, a considerable amount of relevant mission analysis has been done[50]. This has shown that there are only marginal mass advantages to be gained from using vectoring to offset the effects of the assumed ±3 thrust vector misalignments and of the shift of the spacecraft CG. As indicated in Fig.30, an appreciable mass saving of hydrazine, over 6kg, can be achieved for a typical mission, but this is largely balanced by the additional mass of the vectoring equipment, 4kg. However, as larger spacecraft and longer missions are considered, the advantages of using a vectoring system become more pronounced[51], especially if momentum wheel offloading can be achieved using the ion thrusters[50] (Fig.31).

A final decision on whether vectoring is desirable for a particular spacecraft must await a detailed analysis of the mission in question. In particular, the disturbance torques must be known, together with the ion thruster installation arrangement, the type of attitude control system to be employed, and the on-board capability of sensing attitude changes and of computing the required vectoring angles and directions.

1.5.13 Life-limiting factors

It is a reasonable assumption that, with any ion thruster system, the ultimate life-limiting factors are to be found in the thruster itself. This is because the pcu, using space-qualified components, adequate de-rating margins,

and appropriate passive and active redundancy schemes, is likely to outperform the thruster in this respect. In addition, no serious problems are likely to occur with the propellant feed system.

It has long been recognised that any thruster contains a number of critical components which can fail prematurely in a random way, and which are also subject to degradation and ultimate wear-out failure. Each type of thruster is different in this respect, and its failure modes must be considered on an individual basis. For example, the shorting of critical insulators which caused the early failures of the cesium thrusters in the ATS-6 spacecraft[6] is extremely unlikely in a device using mercury propellant.

A comprehensive list of the possible life-limiting factors of a Kaufman thruster using mercury propellant is given below. Although many appear serious, a great deal of life-testing has already been carried out in the UK development programme, and this has shown that the durability of the T4A thruster should be entirely adequate for all likely European missions. This conclusion is heavily backed by the vast amount of life-test experience gained with Kaufman thrusters in the USA[52] over a period of many years. The total must now be more than 100000 hours; it was 60000 hours in 1973. In addition, individual station-keeping thrusters have reached 15000 hours [53] and large primary propulsion thrusters, in which conditions are much more severe, have surpassed 7000 hours[54]. There is, consequently, no reason to believe that this technology is not capable of performing the missions currently of interest.

(a) Accel grid erosion

In the early days of ion thruster development, accel grid erosion by charge exchange and neutraliser ions was a serious problem, as indicated by the SERT II flight experience[21]. However, considerable improvements in knowledge of thruster design and operating techniques have reversed the situation, so that other components are now of greater concern.

As regards the T4A device, a number of features contribute to the long life expectancy of the accel grid. These include the relatively uniform plasma distribution in the discharge chamber, the low neutral efflux, the low neutraliser flow rate, the direction of the flow from the neutraliser cathode orifice, and the low value of V_{ac} employed. The grid life, as estimated by several methods from data obtained during two 1000 hours life tests, is between 20000 and 100000 hours [31].

(b) Discharge chamber sputtering

In a number of recent life-tests in the USA, problems have occurred due to the sputtering of internal surfaces of the discharge chamber by ions, which are usually assumed to be doubly-charged[43]. The sputtering is not usually serious in itself, but it can cause difficulties when material deposited on other internal surfaces becomes detached in the form of thin flakes, with the possibility that they may be responsible for inter-grid shorts[47] and even total failure of the thruster. A particularly serious case arose in the life-test by TRW of a Hughes SIT-5 thruster for Comsat[41].

Several simple methods have been devised to overcome these problems[42]. The most obvious is the use of sputter-resistant materials for sensitive components, such as the baffle disc, and another is to so construct or treat internal surfaces that material deposited on them does not subsequently flake off. As described in section 1.2.8, both approaches have been used in the T4A thruster, with excellent results. In addition, the efficient discharge chamber and ion extraction process, and the flat plasma density profile (Fig.23), combine to minimise the internal sputtering rate.

To summarise the results presented in section 2.2.1, the sputtering observed in a test lasting 2300 hours was very small, and no significant material had flaked away from the internal surfaces of the thruster, despite several unrepresentative exposures to air. Consequently, there is every reason to believe that discharge chamber sputtering does not present a significant problem with this thruster.

(c) Cathode dispenser barium depletion

It is believed at the present time that the gradual loss of barium from the porous dispensers[36] in both the discharge chamber and neutraliser cathodes represents the ultimate life-limiting factor in the Kaufman-type thruster. Although cathodes will operate without barium, the presence of this or of a similar material is essential for easy starting and for running at low values of temperature, flow rate and voltage[10]. The aim is to dispense the barium slowly throughout the mission, so a gradual degradation of performance is expected and observed[35,55] as the amount remaining is reduced, and its dispensation then requires higher temperatures.

Although it is recognised that this is a limiting factor, it does not appear to be particularly serious for the nssk missions of interest. As will

be mentioned in section 2.2.2, a great deal of diode cathode life-testing has been done in the UK, with over 5000 hours achieved on a number of occasions. In addition, he much more extensive life-test experience in the USA suggests that the ultimate lifetime of these cathodes considerably exceeds 10000 hours [53,56,57]. This is particularly true if the temperature of a cathode is kept low, as is the case with large orifices[35], neutralisers[33,37], low discharge currents and good thermal design.

It should be mentioned that one factor has not so far received adequate attention in any cathode test programme, and that is the effect of multiple starts on barium depletion. As these are likely to be equivalent to a significant amount of steady-state running as regards deterioration, an experimental evaluation of their relative importance has commenced. There is, however, evidence from an earlier long series of discharge initiation tests[58] that the overall degradation due to this cause is not likely to be serious.

(d) Cathode orifice erosion

Cathode orifice erosion occurs continually during operation owing to ion bombardment from the coupling plasma. At one time, this appeared to be a serious problem, but it has now reduced very considerably in significance due to improvements in overall cathode design and performance, and to the introduction of larger orifices[36].

It has been established that the electrons emitted by a hollow cathode originate internally[10], and are then extracted through the orifice by the electric field applied by the keeper[35]. The impedance of the orifice to the electron current partially determines the applied voltage needed, and therefore the erosion of the cathode tip through ion bombardment. The effect of orifice size on this erosion is seen in Fig.32. In line with these results, tests of up to 5000 hours duration have indicated that this erosion is no longer a problem for the nssk mission.

(e) Cathode heater reliability

The most highly stressed heaters in the thruster are those on the two hollow cathodes (Figs.4 and 9). If they can be designed to survive a typical mission, there should be no difficulty with the other heaters, which have to withstand much lower power densities, rates of temperature rise, and maximum temperatures.

It has been shown, by extensive thermal cycle testing over several years, that the cathode heater technology described in section 1.2.3 is entirely adequate for the task, provided that proper quality control is exercised during manufacture. As an example of this testing, a cathode has successfully withstood the thermal transient imposed on it by the type of pwm heater power supply incorporated in the pcu for over 5000 thermal cycles. Perhaps more impressive is a test in which a cathode was cycled to a typical operating temperature in about 2½ minutes, more than twice as fast as is required in practice. As shown in Fig.33, the current and power profiles were a very severe test, yet the heater survived more than 5000 cycles.

(f) Isolator breakdown and leakage

Although isolator tests have not so far exceeded 2800 hours [20], there is every reason to believe that no operational difficulty will be experienced with these devices. In all tests performed to date, the leakage current has been below 1mA, more often below 100μA, and this was shown to be entirely due to external contamination; a simple remedy was the addition of sputter shields, as shown in Figs.4 and 6.

Electrical breakdown has not so far been experienced under normal operating conditions, and the possibility of its occurrence is considered small; the factor 4 safety margin on minimum breakdown voltage ensures this (Fig.7). The degradation of this parameter observed in one test[20] was possibly due to the effect of repetitive, deliberately induced, diagnostic breakdowns throughout the test. Post-test analyses indicated that these may have transported metallic particles from the end flanges and brazes into the internal insulating region; this would not occur in actual thruster operation.

(g) Vaporiser porous plug failure

There are three possibilities under this heading. The first, and most likely, is wetting of the plug by a contaminant, such as copper or aluminium. If this occurs, the flow rate passed by the plug at a given temperature will change drastically or leakage of liquid mercury may occur. Both are potentially catastrophic, and can only be avoided by careful cleaning of the tank and all components through which the liquid flows, and by very careful distillation and analysis of the mercury. With good quality control and properly designed cleaning and filling procedures, all problems in this area should be avoided.

The second possibility can also be avoided as described above. It is, in fact, the opposite, where the plug becomes blocked by non-wetting contaminants. This is not so serious, as it would probably occur slowly and the control system would be able to allow for it, within limits.

The third possibility, a mechanical failure of the plug, would probably be catastrophic, although cases have occurred in the laboratory where cracks have not passed liquid, at least at moderate pressures. Again, careful quality control and inspection should eliminate this failure mode.

(h) Insulator leakage

Unlike the case of a cesium thruster, this problem can usually occur with mercury only if sputtered material or 'cracked' pump oils can reach the insulators in question. The remedies are very simple; the provision of adequate sputter shielding and of a well-trapped vacuum pumping system.

With the T4A thruster, the insulators most at risk are those carrying the highest voltages. They are the grid insulators and the keeper insulators. The former were well sputter shielded from their initial design, but the latter were marginal in this respect, until additional sputter shielding was provided. Very good results are now obtained, although tests longer than 1000 hours have not so far been made.

1.5.14 Performance summary

Table 6 contains a summary of the performance achieved by the T4A thruster at its normal 10mN operating point. Most of the data presented were obtained during a 1000 hour life-test. Where appropriate, corrections for doubly-charged ions, neutraliser flow rate and keeper power have been applied; the corrected values are given in brackets beside the uncorrected ones.

1.6 The configuration of future thrusters

Although the overall performance of the T4A thruster is excellent by current standards, and there is every confidence that its lifetime is adequate to meet the requirements of all envisaged missions, it cannot be considered to be a flight thruster in its present mechanical form. In particular, preliminary vibration testing has suggested that redesign in some areas would improve its resistance to damage during the launch phase of a mission, and some constructional methods should be improved in a flight version. There is also the possibility of further weight reduction, although it should be pointed out that the device already has one of the lowest mass/thrust ratios available.

Table 6

Measured performance of UK T4A electron bombardment ion thruster at 10mN thrust
(Pcu excluded)

Thrust	10.5 (10.3)*mN
Thrust range without performance degradation	7 to 17mN
Exhaust velocity for singly-charged ions	30km/s
Specific impulse	2744 (2625)s
Total input power (neutraliser bias = 0)	223W
Power/thrust ratio	21.3 (21.7)W/mN
Total mass flow rate	0.390 (0.400)mg/s
Energy cost per beam ion	237 (287)eV/ion
Electrical efficiency	70.7%
Mass utilisation efficiency	89.5 (84)%
Total thruster efficiency	63.3 (59.4)%
Semi-angle of beam divergence at 95% of I_B	<11°
Beam accelerating potential	940V
Beam current	167mA
Accel grid potential	300 to 400V
Accel grid current	<0.5mA
Anode potential	39.7V
Discharge current	1.0A
ΔV = anode potential - keeper potential	28.6V
Keeper current	0.6A
Neutraliser flow rate	~0.01mg/s
Neutraliser keeper current	0.3A
Neutraliser bias potential	0
Backplate temperature	~130°C
Mass, excluding mounting structure	1kg
Start-up time	~10min
Length (neutraliser tip to vaporiser inlet)	20cm
Diameter of earth screen	19cm

* Values given in brackets have been corrected for doubly-charged ions, keeper power, and neutraliser mass flow, where appropriate.

The initial attempt at the redesign process, designated the T5 thruster, is shown in section in Fig.34. The main criteria laid down for this design were:

(a) No changes were permitted to the discharge chamber dimensions, configuration, or magnetic circuit which might alter the performance from the standard set by the T4A thruster.

(b) No changes were permitted to the grid materials, hole sizes, separation or dishing.

(c) The T4A cathode/isolator/vaporiser assembly and neutraliser assembly were to be incorporated without change. Minor changes were permitted to the main flow vaporiser/isolator assembly.

(d) The mounting system was to be designed to be compatible with the use of gimballing for thrust vectoring, should this be necessary, and with a remote propellant tank installation.

(e) Any major modifications must have evidence supporting their compatibility with criterion (a) above.

Consequently, the discharge chamber is largely identical to that of the T4A thruster, minor modifications having been introduced only to the front pole, to improve vibration resistance of the grid structure, and to the distributor, to take advantage, during start-up, of the heat available from the hollow cathode. At the time of writing, it has already been shown experimentally that the changes to the front pole and the necessary consequential modifications to the solenoids have not altered the performance from that obtained with the standard T4A thruster.

The potential vibration resistance of the grid assembly has been improved in a number of ways, apart from the modifications to the front pole. In particular, the edges of the accel grid mounting lugs have been made stiffer by bending their edges over at 90° to the plane of the grid. In addition, the mounting point of the assembly has been altered from that used in T4A; independent compliant strips now join the assembly to the front pole. Previously, the bent-over tabs of the screen grid were used for this purpose (Fig.2), which was rather inconvenient should alterations to this mounting scheme be required.

The other main changes from the T4A design are to the rear of the thruster, largely because an integral tank is no longer a requirement. Deletion of this component has allowed the dimensions of this region to be considerably reduced,

and the main mounting is now provided by a strong ring separated from the backplate by six insulators. The enclosure to the rear of the backplate is structural in that it supports the rear end of the cathode isolator, but its main purpose is to act as a radiation shield, to minimise the amount of heat transferred rearwards to the spacecraft. The other change in this area concerns the main flow vaporiser/isolator assembly, which now has a right angle bend between its two components.

It must be emphasised that this design is not thought of as the final flight thruster, although it is expected that it will provide a sound basis for any further development. This development is described in section 3, where it is also pointed out that a further significant design change will be necessary if it is found possible to fit a redundant discharge chamber cathode: redundant neutralisers and mainflow assemblies are already catered for. Timescales are such, though, that this will not be feasible before the 1983 operational launch; a direct derivative of the T5 device must be employed for the 1980 test flight.

It is not easy to include a spare discharge chamber cathode, because an angled configuration will probably have to be employed, and this may influence the coupling plasma to such an extent that performance is degraded. Consequently, a considerable amount of effort may be needed to arrive at a satisfactory design of this device, which is designated T6 in section 3. Although success is not guaranteed, the benefits to reliability of being able to fit a redundant cathode are sufficient to make this additional development worthwhile.

1.7 Associated technology

During the project which has culminated in the design of the T4A and T5 thrusters, a considerable amount of ancillary development has taken place, particularly of instrumentation. As some of the devices in question may have wide application during thruster testing, check out procedures or even in flight, these are described below. Many others have been omitted.

1.7.1 Thruster simulator

This complex analogue device[59] uses an arrangement of interacting diode function generators and amplifiers to closely simulate the steady state and dynamic performance of a thruster, and thus to correctly load a power conditioner under virtually any reasonable conditions. It was originally designed to simulate an early RAE thruster, but has now been modified to represent T4. As well as being available to load the power conditioner and thus test it under

accurately realistic conditions, the simulator can also be employed to study new control system concepts and the effects of component degradation during thruster operation. In addition, it could help in examining abnormal operating conditions and throttling techniques. Most of these proposed uses are of potential benefit because they could reduce development costs and timescales by, for example, significantly decreasing the amount of thruster operation required to solve a particular problem. The application of pcu check-out is of direct benefit, however, because a pcu mounted in a spacecraft cannot be ground tested by running the appropriate thruster and, consequently, some type of thruster simulator must be employed. Ideally, this simulator should load the pcu realistically under all conceivable operational conditions, and the achievement of this objective has been a major aim.

Analogue simulation was chosen because of the ease of manipulation offered by this method, which proved particularly useful in the initial stages of formulating the design, as did the absence of software and analogue/digital interfacing. Furthermore, simulation could be easily derived from the static characteristics of the thruster, whereas the thruster was not generally well enough understood to adequately describe mathematically. However, this is not considered to be a definitive approach and, having achieved the initial goal of establishing the design concept, it may eventually prove necessary to change to other simulation methods if future experience should prove it desirable. For example, in the present design, using diode function generators, care was necessary to minimise tracking errors which arise from diode threshold voltage shifts with ambient temperature variations. This could be avoided by perhaps the more elegant approach of using digitally controlled function generators.

A schematic block diagram of the simulator is shown in Fig.35. As already mentioned, it is based on the exact analogue representation of measured thruster characteristics by diode function generators (DFGs). Those shown in Fig.35 represent the following functions:

G1 the output represents the main vaporiser flow rate $\dot{m}_M$ as a function of vaporiser current I_{VM}

G2 the output represents the hollow cathode vaporiser flow rate $\dot{m}_{HC}$ as a function of vaporiser current I_{VHC}

G3 simulates the variation of ΔV as a function of solenoid current I_m for a range of total flows $\dot{m}_T = \dot{m}_M + \dot{m}_{HC}$, at a standard arbitrary discharge current I_{D0}. The output is designated ΔV_0.

G4 simulates the dynamic impedance of the discharge chamber, $\delta(\Delta V)/\delta I_D$, at I_{DO} . This representation is valid because the impedance change is linear over a wide range of I_D and is not strongly dependent on $\dot{m}_T$.

G5 represents the variation of η_m as a function of ΔV for an extended range of values of I_D . The actual characteristic used is fixed by the output of G6; this is possible because the characteristics are parallel and of the same shape.

G6 determines the value of η_m appropriate to the computed value of I_D , at an arbitrary pre-set value of ΔV, ΔV_S .

G7 simulates the beam current produced by the computed values of η_m, I_D and ΔV for the given value of $\dot{m}_T$. It effectively multiplies η_m by $\dot{m}_T$, but also introduces the 'break-points' between the linear regions of the I_B-$\dot{m}_T$ characteristics.

In section 1 of the present simulator, signals appropriate to the vaporiser heater currents I_{VM} and I_{VHC} are fed into G1 and G2, which simulate the appropriate thermal delays as well as the variation of flow rate with heater current. The simulated flow rates are passed to G3, which also receives a signal representing I_m . The output of G3, representing ΔV_0 as a function of the flow rates and magnetic field, is used in conjunction with G4 and multiplier M to derive a signal simulating the amount $\delta(\Delta V)$ by which the actual value of ΔV in the thruster deviates from ΔV_0 due to a deviation δI_D from an arbitrary standard, I_{DO} . Differential amplifier A1 is used to give δI_D ; it compares an input representing I_{DO} with another representing I_D derived at a later stage in the simulator. $\delta(\Delta V)$ is then added to ΔV_0 to give the actual value of ΔV appropriate to the inputs in use, although a negative output is provided.

Section 2 uses the derived value of ΔV to provide the appropriate loading to the current-controlled discharge power supply; the principles employed here can be used in a similar manner for loading the other supplies. Basically, the loading regulator is driven until the difference between the applied values of the anode and keeper voltages, V_A and V_k , is equal to ΔV . A signal representing the resulting value of I_D is then passed from amplifier A2 to section 3, also back to A1.

Section 3 generates I_B as a function of $\dot{m}_T$, I_D and ΔV, by first deriving the value of η_m appropriate to the inputs, in a two-stage process. In the first stage, G6 is used to find the value of η_m appropriate to the value of I_D already obtained, at some arbitrary fixed value of ΔV, ΔV_S. This value of η_m is then inserted into G5, at the set voltage ΔV_S, to determine the actual position of the appropriate characteristic in that DFG; this is a valid procedure because the wide variety of possible curves are all approximately parallel, there is merely a move upwards or downwards with change of I_D. The final DFG, G7, multiplies the value of η_m appropriate to the value of ΔV, computed by section 1, by $\dot{m}_T$, and modifies the result in accordance with the detailed shape of the thruster's beam extraction characteristics to give I_B.

The overall accuracy of the simulation is excellent. As an example, T4 thruster and simulator performance maps are compared in Fig.36, where it can be seen that a ±5% agreement is achieved over a very wide range of conditions. Similar results are attained if other parameters are compared.

1.7.2 Electromagnetic sequencer

Although all cyclic testing of thrusters will eventually be performed using pcus, and the start-up and shut-down procedures will be controlled by sequencers based on microprocessors, a need exists at the present to conduct tests of this sort with laboratory power supplies. These are life-tests of the type specified recently by Comsat[15], which are intended to provide preliminary information concerning the durability of thrusters and components prior to the availability of pcus of proven reliability.

It is, of course, possible to carry out cyclic testing of this type under manual control, but this is prohibitively expensive if the aim is to achieve hundreds or thousands of cycles. Consequently, an electromechanical sequencer has been designed and constructed which will carry out these functions completely automatically, following the same programme of events as does the pcu sequencer (sections 1.3.3 and 1.5.7). It is currently installed at the Culham Laboratory, where it will be used to test a T4A thruster for about 1500 fully automatic thrusting cycles, with extremely comprehensive beam diagnostics.

This sequencer has been designed by RAE to connect laboratory supplies to the thruster in a defined manner, using, as switches, a number of reed relays (of breakdown voltage in excess of 5kV and of 3A current rating). As shown in

Fig.37, the operation and release of these robust devices is controlled by two uniselectors, which supply 'operate' or 'release' pulses as required. The relays are used in a latching mode and make use of a 'hold' coil passing a current that is common to all relays of a set. Thus relays can be released by a general 'drop out' command as well as by a 'release' pulse.

Where appropriate, adjustment of thruster power levels is arranged by switching series resistors. For example, in the case of the hollow cathode tip heaters, the initial current to the (cold) heater winding is limited by series resistors that are short circuited in steps as the hollow cathode warms up, thus reducing the possibility of cathode degradation due to thermal shock. The power profiles shown in Fig.19 are followed approximately.

As in the pcu sequencer, the programme of switching events is partly a function of time and partly a function of the state of the thruster. Both the uniselectors and the reed relays are rugged devices that are not susceptible to damage by transients. They have well defined lifetimes that are several orders of magnitude greater than the test lifetime requirements. One uniselector is used to control the switch-on of the neutraliser sub-system while the other switches on the rest of the thruster. The uniselectors have a considerable number of positions in excess of requirements, which are distributed to allow for any additional switching functions should these later become necessary. The device thus provides good versatility.

Closed loop controllers are also included in the sequencer package because it effectively determines the time at which the loops are closed, and also because the controllers take the form of reed relays that are switched by a low frequency pulse width modulated system[38].

The timing electronics will permit switching intervals which can be as short as the uniselector response, say 100ms, or as long as many minutes. This feature also provides versatility.

A simplified version of this device is being produced for use in cathode and neutraliser cyclic life-testing. For this application, relatively few power supplies are involved for each component tested, but several simultaneous tests are needed to gain reliability statistics.

1.7.3 Thermal flowmeter

Although it is not usually considered necessary to measure the propellant flow rates to a Kaufman-type thruster when used in the nssk application,

especially when it has dual discharge chamber control loops (section 1.3.4), flow measurements are essential in laboratory tests of both thrusters and individual components. Such measurements are usually made by observing the rate of fall of a mercury meniscus in a capillary tube, but this is a laborious technique, it does not provide a continuous reading, and it is inaccurate unless great care is taken in applying corrections[35]. In addition, there are some possible ion thruster missions where propellant utilisation efficiency must be maintained constant over very long periods of time, implying that the use of a flow monitoring device is essential.

For these reasons, a thermal flowmeter has been developed[11] which is small, light in weight and potentially capable of flight qualification. In addition, its power consumption is very small. In this device, the experimental version of which is shown schematically in Fig.38, the centre of a small diameter, thin walled flow tube is heated to temperature T_1, while the ends are maintained at a lower temperature T_2. Symmetrically positioned temperature sensors (at points E and F in Fig.38) between the heater and cool ends register unequal outputs when flow occurs along the tube, owing to the heat transported preferentially in one direction by the movement of the liquid. The difference between the outputs of the sensors is linearly related to flow rate, provided that $(T_1 - T_2)$ is maintained constant. Power dissipation is below 1W, for $(T_1 - T_2) \sim 250^\circ C$.

The experimental results agree reasonably well with theory[11], which also suggests that thermal shunting by the tube wall reduces sensitivity, so considerable effort was devoted to reducing its thickness. This theory has also been used to determine the optimum positions of the sensors.

At the present time, Mullard Ltd. is developing the experimental device to increase its sensitivity and accuracy, mainly by employing sensors of a higher output than the thermocouples originally used; they gave a sensitivity of 0.8mV $(mg/s)^{-1}$, without amplification, with $(T_1 - T_2) = 250^\circ C$. Accuracy is being enhanced by improvements to the thermal coupling between the two cold ends of the flow tube and by an overall raising of the standard of the manufacturing techniques employed. In addition, the device is being made more robust and its overall size is being reduced, possibly to about 1cm diameter and 3cm long. The electronics package being produced simultaneously contains an accurate temperature controller to ensure that the heater power is correctly adjusted at all times to keep $(T_1 - T_2)$ constant, together with appropriate stable amplification for the signals from the sensors.

2 DEVELOPMENT STATUS REVIEW

This section commences with a summary of the long development history of the UK 10cm Kaufman-type ion thruster, in which it is shown that active work has continued in a logical, uninterrupted, manner for a period of about nine years. Throughout the project, emphasis has always been laid on attempting to understand the basic physical principles governing the operation of the thruster and of its important components. The aim of this approach, which differs fundamentally from that adopted in a number of other organisations dealing with similar devices, was to gain sufficient design information to be able to avoid the entirely empirical methods which are so costly of time and resources.

It is also shown in the history presented below that all parts of the thruster system have received adequate attention throughout the programme, when taking into account the different development needs of those separate parts and the likely timescale of applications of the system. Obviously, the thruster itself has been the subject of the greatest effort, although a very large amount has also been devoted to critical components, notably the hollow cathode. Other important parts of the total thruster system, such as the pcu and tank, were not concentrated on until much later, for two separate reasons. The first reason, applicable to the pcu, was that adequate design information was not available early in the programme, so there was little point in commencing the development of a device that would almost certainly become obsolete later as more precise data were produced. The second reason, applicable mainly to the tank and valves, was that a clear development path could be envisaged for such components, which was relatively free of major difficulties, so the deployment of resources into these areas could be safely delayed until nearer the date of the first likely mission.

As performance aspects of the system have been thoroughly covered in section 1, only the life-testing carried out to date is described in this section. This life-testing has concerned both thrusters and critical components. However, the review given concentrates mainly on the two separate 1000 hour tests so far completed of a T4A thruster, which indicate that its durability is probably adequate for all likely future nssk missions. This conclusion is supported by the separate tests of many components, which have been extended successfully to much longer durations. For example, cathodes have achieved in excess of 5000 hours and vaporisers 12000 hours.

An important second conclusion of the thruster tests, which is also described, is that the material sputtered from the accel grid is unlikely to cause significant solar array degradation, even over periods of 5000 hours. This therefore confirms that a major potential contamination problem, which has always greatly concerned spacecraft designers, is probably not a handicap to the use of the T4A thruster or its derivatives.

Although the remainder of the development programme, which is discussed in detail in section 3, is very extensive, no fundamental problems can be foreseen. Most of the work is of a fairly routine nature, such as 'packaging' the pcu for flight and formally space qualifying the many parts of the thruster system. Of course, significant problems may arise during any part of this programme, particularly as a result of the comprehensive cyclic life-testing included, but they cannot be predicted at present. Consequently, the discussion of such problems in section 2.3 is rather brief and speculative, but this can be taken as an indication of the present advanced state of the project.

This section concludes with a description of the test facilities available in the UK for ion thruster development, and also a complete bibliography. The existing test facilities are considered to be nearly adequate to complete the project to operational status. They include, at present, two facilities capable of meaningful life-test work, and plans are included in section 3 for the purchase, by MSDS Ltd., of another facility for this purpose. The Culham life-test facility is described in most detail, because it is probably the best of its type in the world, being capable of almost every conceivable diagnostic of the exhaust plume of a thruster.

2.1 Brief history of development

Theoretical studies of electric propulsion systems and their applications to both primary propulsion and station-keeping roles for various satellite missions were started in the RAE about 1962. Over the next few years several reports on these subjects were published, which showed that considerable advantages would follow from the introduction of electric thrusters, provided that adequate reliability could be attained. In particular, it was found that very large benefits could be obtained from the use of an ion thruster to raise the orbit of a satellite by thrusting for a long period in the direction of motion[60]. It was suggested that the capabilities of the UK Black Arrow launcher could be considerably enhanced by the use of this technique.

As a result of these studies, early in 1967 a team was formed in Space Department, RAE to undertake and lead the development of various electric propulsion systems. In particular, rail guns using mercury, arc jets and mercury bombardment thrusters were investigated. Although some of this work was pursued for several years, it is unnecessary to go into further details of all the systems explored, as the UK programme has concentrated for a long time on the Kaufman-type mercury bombardment thruster. In view of the interest generated in improving the payload capabilities of Black Arrow and, incidentally, of the various ELDO launchers, the development of the bombardment type thruster was initially aimed at producing a 10cm diameter, 15mN thruster for spiral orbit transfer manoeuvres. However, in 1970 a policy decision was made to stop the development of primary propulsion systems, so the ion thruster work was realigned to produce a 10cm diameter, 10mN thruster for station-keeping purposes. The objectives of the programme have not changed since.

It should be mentioned here that the choice of a 10mN thrust level was made after very careful consideration of all possible missions, and it appeared to offer the greatest versatility. At the time that this decision was made, nearly all other developers interested in nssk and similar missions had concluded that much lower thrusts were optimum; a typical result of this reasoning was the NASA/Hughes SIT-5 thruster[45]. What they appear to have ignored, in concentrating unduly on thruster power consumption, is the long operating times needed by these small thrusters[2], which therefore require extreme durability of all components and, consequently, very long and expensive ground life-tests. In retrospect, the RAE choice of 10mN has been validated by subsequent events and analyses[2,15,51], but it should be emphasized that the thrust level can be changed over a wide range without modification to the thruster.

Although the RAE has been responsible for the technical direction of the project from its beginning, and has also done a large amount of the research, development and design work, several other UK organisations have been extensively involved for many years. In general, these organisations provide complementary expertise which has been combined very effectively to produce an impressive overall capability in the ion thruster and allied technological fields.

It was recognised at the beginning of the development work that it was very desirable to involve industry in the manufacture of highly specialised parts of the thruster, such as cathodes, vaporisers and grids. Accordingly, since April 1968, many contracts have been placed on the Central Materials Laboratory of

Mullard Ltd. for the development and manufacture of thruster components. This work has been done in close collaboration with the RAE, which has done the majority of the basic, exploratory studies. Both organisations are still actively involved in component development and life-testing.

Early in the experimental programme it was also realised that considerable help could be provided by the plasma physicists at the UKAEA Culham Laboratory. Accordingly, an agreement was made with Culham whereby the Laboratory's Ion Physics Group played the leading part in the investigation of the physical phenomena of the thruster and provided corresponding design and manufacturing support to the RAE, which was also engaged in developing the thruster and its components. Culham staff have been actively engaged in this role since 1969, and, as will be seen in section 3, the Laboratory also has a major contribution to make in any future comprehensive programme of work.

In addition to work on ion bombardment thrusters in conjunction with the RAE, Culham has undertaken R&D work on both colloid and field emission thrusters for ESRO[61]. Southampton University has also been involved in this project[62].

By 1972, the electrical requirements of the thruster were sufficiently well known to prepare a specification for a 'breadboard' pcu, including the starting sequencer and a telemetry system. A contract for the development of this unit was placed on MSDS Ltd., and integration of the resulting system with T4A thrusters was commenced in 1974 and continued into 1975. This integration exercise was carried out at Culham and at the RAE, although plans now exist for MSDS to procure their own test facility (section 3). It is worth pointing out here that MSDS Ltd., then Elliott Brothers Ltd., was interested in ion thruster development prior to 1972, having privately funded a considerable amount of experimental work in this field and in pulsed plasma thrusters as early as 1968 [63].

Considerable further thruster testing has been done by several UK organisations since the original pcu specification was written and, as a result, it is now known that the electrical requirements need to be modified slightly. A contract has been negotiated with MSDS Ltd. for updating the pcu and sequencer to meet the latest thruster starting and operating requirements. The next phase in the development of the electronic system is to package this equipment in a form suitable for flight, and preliminary design work in this area has been carried out by MSDS.

Fairly early in the development work it was recognised that the critical components of the thruster, from the aspect of its reliability, were likely to be the cathodes and grids. It was not difficult to undertake extensive life-tests of cathodes, as the apparatus required was comparatively small. However, to subject the grid system to meaningful tests requires the grids to be mounted correctly on an operating thruster. In addition, the environmental conditions in the thruster test chamber have to be carefully controlled, to avoid obtaining spurious results. Accordingly, a contract was awarded in 1970 to the Fulmer Research Institute to design, build and prove a complete thruster test rig with a mercury pool target, specifically for examining the erosion of the grid system during extended running. Advantage was taken of this facility to provide apparatus for examining some of the external effects produced by the ion beam.

Following very satisfactory evaluation of the viability of this test rig, two 1000 hour runs were successfully completed on a T4A thruster in 1974 and 1975. These life-tests showed that the grid life was appreciably in excess of that required for operational use, and also showed encouragingly low contamination of sample surfaces which were placed near the ion beam.

It should finally be mentioned that the isolators employed so successfully in the T4A thruster are produced by Anderman and Ryder Ltd. The concept used in the operation of these devices was evolved by the RAE[25], whilst the constructional techniques were developed by the firm, a contract being awarded for this work in 1970.

2.1.1 Early thruster development at the RAE

As shown in Fig.39, which summarises the UK ion thruster project from its beginning to the present date, experimental work started in the RAE late in 1967 on a simple Kaufman-type thruster[64], designated T1. The design of this device was based partly on a theoretical analysis of the physical processes thought important to the operation of a thruster of this type, and partly on a critical review of relevant American experience. As this was a first attempt at producing an experimental thruster, no effort was made to minimise mass or size, or to achieve long life or vibration resistance.

As originally designed, the thruster was fitted with an axial thermionic cathode, and the magnetic field used for containing the discharge chamber plasma was produced by a pair of external coils. No neutraliser was fitted and a single vaporiser supplied mercury vapour to the discharge chamber, via a

distributor. To illustrate the enormous progress made since that time, a photograph of the thruster is shown in Fig.40; it should be compared with the T4A thruster illustrated in Fig.3.

Testing was carried out in the RAE 0.9m diameter by 1.8m long facility (section 2.4.2), and it was soon confirmed that the durability of the thermionic cathode was entirely inadequate. Since this had been foreseen, it had already been decided to initiate work on the production and further development of hollow cathodes, starting from devices similar to that used in the SERT II thruster[21,29]. It was therefore possible to fit such a cathode to T1 in 1968, and the opportunity was also taken to include a dual vapour flow system to the discharge chamber, using improved vaporisers[24], and an inner polepiece/baffle disc assembly.

In this form, tests on the T1 thruster continued into 1970. Much useful information was obtained and it was confirmed that a high performance could be achieved. In particular, some of the criteria important in thruster design were established. For example, it was found that three regions exist within the thruster which are sufficiently de-coupled to allow them to be treated separately, to first order; they are the plasma within the inner polepiece, the discharge chamber plasma, and the ion extraction region. The role of discharge instability limits was determined, especially those associated with the acceleration of the primary electrons, and the use of the total ion current to the plane of the screen grid as an indicator of discharge chamber performance was explored. It was established that a low screen grid open area ratio and a peaked plasma density distribution were detrimental to high ion extraction efficiency.

The final performance achieved with the hollow cathode was encouraging, with $\eta_m > 90\%$ at 530eV/ion, and 70% at 400eV/ion. This was nearly 600eV/ion better than with the original thermionic cathode at a given η_m.

The data obtained from testing T1 were used in the design[65] of the T2 thruster, which was intended to give improved performance, together with reduced mass and size. A number of the refinements introduced into this design from the outset were of fundamental importance, and contributed to the success of later thrusters. They included the use of properly integrated twin feed systems to the discharge chamber, with appropriate thermal decoupling of the vaporisers. In addition, a magnetic circuit based on SERT II was incorporated, although the flux was generated by solenoids rather than by permanent magnets; six separate

solenoids around the periphery of the thruster were used, or, alternatively, a single coil wound on the discharge chamber. A life-test model[55] also incorporated a hollow cathode neutraliser and experimental electrical isolators[25]; both behaved well during life-testing.

In addition, it was during tests of this type of thruster that thermal problems associated with the grid system were solved by the introduction of dishing.

The hollow cathodes used were of the relatively simple laboratory type[29], but the barium dispenser was progressively improved during the test programme, so that greater reliability could be attained. A further contribution to this was made by improving heater technology and by the use of cathode radiation shields.

Four T2 thrusters were constructed, two by the RAE and two by the Fulmer Research Institute. One of those made by Fulmer was extensively used in the calibration of the life-test facility installed at the Institute[66], the other being employed for demonstration purposes. At the RAE, one thruster was extensively involved in development work, while the second was life-tested to 1700 hours, with 177 starts[55], using a small, purpose-built facility. This life-test demonstrated that long duration runs with many starts were quite feasible, and that the addition of a neutraliser and isolators did not cause extra problems. During part of the test, the beam was powered by an early flight-type modular supply[12], which performed very well.

As regards the development work accomplished with the other RAE T2 thruster[65], it was confirmed at the outset that the conclusions reached at the end of the T1 studies[64] had been valid. In particular, the separation of the thruster into three regions was shown to be a useful concept, and the importance of the inner polepiece/baffle disc region to the overall performance was also confirmed. An attempt was made to separately control the fringing magnetic field in this region, using a coil on the cathode pole, so that the magnetic field employed to contain the discharge chamber plasma could be adjusted independently of the field dominating the primary electron acceleration process. Although successful, this technique did not allow any significant performance gains to be made, so it was not adopted in later designs.

The most significant result obtained probably concerned the ion extraction system. It was confirmed by using screen grids with different open area ratios

that τ has a very great influence on the ion extraction efficiency and thus on overall thruster efficiency. In particular, as shown in Fig.41, increasing τ from 50% to 70% and beyond gave a dramatic improvement in ε for a given η_m ; consequently, later work concentrated on values of τ above 70%.

Much additional work was carried out with this thruster. This included the first investigations of the dual discharge chamber control loops, the influence of hollow cathode parameters on control, and the variations of instability limits brought about by changes in thruster conditions. In addition, preliminary studies were made of the heating and cooling of a thruster during cyclic operation.

In mid-1971 sufficient information had become available from these tests and from the plasma physics investigations at Culham for the design of a more advanced thruster, the T4, to be commenced. This joint design is covered in section 2.1.3.

It should perhaps be mentioned that a T3 thruster was designed by the RAE and was constructed by GEC Ltd., although it was never operated. It was, basically, an improved T2, and incorporated a conical discharge chamber to reduce the internal area to which ions can be lost. The latter feature was transferred eventually to the T4 design. The T3 thruster was not tested due to the very considerable extension of the studies and updating of T2 following the remarkable increase of performance caused by the introduction of large open area screen grids.

2.1.2 Plasma physics investigations at the Culham Laboratory

During 1968 and the first few months of 1969 the Ion Physics Group of the Culham Laboratory prepared a 1m diameter by 2m long horizontal vacuum facility for testing ion sources. This facility was equipped comprehensively with Langmuir and ion beam probes and, in addition, all internal surfaces, notably the target and cryoshrouds, were instrumented to allow the currents collected by them to be measured. At the same time, a 15cm diameter ion source, designated C1, was being prepared for test. Although based on the SERT II ion thruster[21] as regards dimensions, it was instrumented with probes and ionisation gauges, and all components in contact with the plasma or ion beam were electrically isolated and capable of being biased.

The hollow cathodes used came from several different organisations as testing progressed, GEC Ltd., Mullard Ltd., the RAE and Culham itself.

Rather surprisingly, at the outset of the experimental programme, very little was known about the fundamental physical processes occurring in the SERT II type of thruster, despite the fact that a flight test was due to take place in 1970. However, the tests at Culham were to alter this situation completely, so that by the beginning of 1972 a very good understanding had been reached of the relevant physics. In achieving this, the Culham team made several notable contributions to the theory of Kaufman thruster operation, particularly concerning the ion extraction mechanism, the acceleration of the primary electrons, and the role of the coupling plasma.

Testing of the C1 thruster commenced with the usual study of performance and operating characteristics. It was found that the performance was very good over a wide range of conditions[7], exceeding a target specification tentatively proposed by the RAE in 1969. At an exhaust velocity of 32.5km/s, ε was below 300eV/ion at $\eta_m = 80\%$, and $\eta_m > 85\%$ was achieved at 400eV/ion.

The next stage of the work included a comprehensive exploration of the importance of the different operating parameters. For example, the performance of the grid system was studied as a function of both thruster and accel grid potentials. An early result, confirming a conclusion reached at the RAE, was that the ion extraction process is not strongly dependent on the conditions in the discharge chamber. A study of the ion and electron fluxes to all parts of the thruster then followed, and the resulting information, when combined with plasma potential and particle energy measurements, also allowed energy fluxes to be derived[7].

As a consequence of these early measurements, the grid work was considerably extended in late 1970, both theoretical studies and experiments on several different systems being undertaken. In parallel, theoretical work on ion beam optics was also in progress at the RAE. The main conclusions were that the screen grid should have a high open area ratio and be as thin as possible (Fig.42) to maximise η_m. In addition, it was established that the shape of the plasma sheath at each screen aperture is important; it was found that a concave shape can lead to an effective value of τ greater than the geometrical value. The plasma density profile within the discharge chamber was also found to affect the performance of the grids; this was the only significant factor which could not be explicitly included in the grid scaling laws[16] formulated as a result of these investigations.

In the next phase of the work at Culham, the thruster was modified to contain a more extensive set of internal Langmuir and wall probes. In this form it was designated C2. After a performance check, which revealed the importance of cathode plasma potential in determining the overall efficiency of the thruster, a lengthy study was made of the behaviour of the coupling plasma and of the mechanism by which primary electrons are produced and accelerated. The electron temperature and number density and the plasma potential were measured throughout the coupling plasma, the main discharge plasma, and in the annular gap between the baffle disc and the inner pole (Fig.1). It was found[9] that the electrons in the coupling plasma had a Maxwellian velocity distribution and that the plasma potential was approximately equal to keeper potential. In the discharge chamber, the velocity distribution was non-Maxwellian, being formed from a fast group of primary electrons and a second Maxwellian group. In that region, plasma potential approximated to V_A. This group of primary electrons was accelerated in the very thin (~1mm thick) region around the baffle disc, and a theoretical explanation of the mechanisms responsible was proposed, which was reasonably consistent with the experimental data[9].

The main result of the work done with the C1 and C2 thrusters was the formulation of scaling laws[8,16], together with generalised design criteria, which enabled later thrusters to be produced without resorting to expensive, reiterative empirical studies of experimental devices. The usefulness and accuracy of these laws were examined practically by designing[8], constructing and testing the C3 and T4 thrusters. As the T4 and its derivative, the T4A, are covered below, the present discussion will be confined to C3.

The C3 thruster was designed by Culham to be a diagnostic equivalent to T4. Consequently, while approximating as closely as possible to T4 in its configuration and dimensions, its construction was very different, following closely the principles which had been so successfully applied in the C1 and C2 thrusters. All parts in contact with the plasma were capable of being electrically isolated and facilities for detailed probing were provided. The device was ready for operation early in 1972.

The performance obtained from the thruster fully validated the scaling laws and the design procedure used. As shown in Table 7, the experimental parameters generally agreed with those predicted during the design work to better than ±10%.

Table 7

Comparison of predicted and measured operating parameters for the C3 thruster

Parameter	Predicted value	Measured value	Units
Propellant utilisation efficiency η_m	0.87	0.87*	-
Ion production energy	227	245	eV/ion
Beam accelerating potential	940	940*	V
Beam current I_B	160	167	mA
Cathode mass flow rate	0.101	0.160	mg/s
Total mass flow rate (excluding neutraliser) $\dot{m}_T$	0.382	0.398	mg/s
Thrust	10.0	10.4	mN
Accel potential	-550	-600 ± 50	V
Accel current	<0.7	0.54	mA
Discharge current $I_D = (I_A - I_B)$	0.88	0.97	A
Anode current I_A	1.04	1.14	A
Keeper current I_k	0.40	0.40	A
Anode potential V_A	41.4	42.2	V
Keeper potential V_k	13.0	14.1	V
$\Delta V = V_A - V_k$	28.4	28.1	V
Maximum magnetic field B_m	7.1×10^{-3}	6.8×10^{-3}	Tesla
Discharge current stability margin	>0.10	0.10*	-
Magnetic field stability margin	>0.10	0.12	-

* Thruster operated at these values

After establishing that adequate performance had been achieved, C3 was used in a series of tests to determine whether improvements could be made, without compromising the basic stability and flexibility of the design. Extensive probing was carried out as each change was made, so that a full understanding of the phenomena observed could be obtained. It was shown that a broad plasma density distribution could be achieved at the screen grid, that a throttling range of 6 to 13mN could be attained, and that very widely separated stability limits could be introduced, but all these could not be fully realised simultaneously. This experience proved invaluable in later attempts to improve the performance of T4 in similar r spects.

C3 was also used in a detailed experimental programme to determine the beam characteristics produced by dished grids. This showed that focussing near the grids was occurring (Fig.10) and suggested that accel grid compensation[30,40] should be used to give a beam shape closer to ideal. In addition, some work was included on the effects to be expected from the expansion of the grid system on start-up of the thruster, and a theoretical analysis of the mechanisms of accel grid erosion was carried out. In the latter study, the influence of the neutraliser was considered, and scaling laws for erosion were evolved.

2.1.3 The T4 and T4A thrusters

Following the experience described above with the T2, C1 and C2 thrusters at the RAE and Culham, and the formulation of physically-based scaling laws[8,16], it was possible, in mid 1971, to commence the design of the first flight-type thruster, the T4. Although based to some extent on T2, this jointly-conceived design was completely new. As its configuration and construction have been described in detail in section 1.2, only the important constraints imposed during the design process will be mentioned here. It should be noted that C3 was designed and constructed, from the same data, a few months earlier.

These constraints included the need to provide a thrust of 10mN at an exhaust velocity of 30km/s from a device of 10cm nominal grid diameter and of minimum mass and power consumption. It also had to be capable of being mounted in a Black Arrow spacecraft as a single package, including propellant supply, and the heat transfer from the thruster to the spacecraft had to be minimal. A start-up time of 5 minutes was originally specified, together with a mass utilisation efficiency of 85%.

Five basic thrusters were initially produced in 1972 and 1973, four by Culham and one by the RAE. Most of the cathodes, isolators and vaporisers, were supplied by the RAE or by Mullard Ltd.

The initial tests of a T4 thruster were carried out at Culham early in 1973 and showed that it was exceptionally stable and that its performance was good, but not quite reaching the standard set by C3 at the specified 10mN thrust. However, at higher thrusts a considerable improvement was realised. For example, the specified value of η_m, 85% at 250eV/ion, was achieved at 12mN; at 10mN, however, η_m was 3 to 5% lower than with C3. Although not serious, this discovery, which was confirmed by other tests at the RAE, prompted a further investigation of the physics of the discharge chamber[19].

By measuring ion flux distributions to all components and the variation of electron current with position along the anode, together with Langmuir probe diagnostics, it was found[19] that minor differences in the discharge chamber geometries and magnetic field distributions were responsible for a significant discrepancy between the ionisation efficiencies in the two thrusters. Primary electrons were reaching the end of the anode nearest the grids too easily in T4, causing the plasma density for a given discharge current I_D to be lower than in C3. Consequently, the anode geometry and position were revised. Space limitations of the original conical design[18] caused a reversion to a cylindrical shape when these modifications were made; in this form the thruster has the T4A designation (Figs.2 and 3).

These changes improved the performance to the level shown in Fig.20, in which it is evident that $\eta_m > 90\%$ at 250eV/ion was achieved near the stability limit, and gave a much flatter plasma density profile (Fig.23, curve a). It should be emphasised that these results, together with exceptional stability, were all achieved simultaneously. Although these individual aims had been realised singly in experiments on C3, it had not been found possible to arrive at a satisfactory balance between efficiency, discharge uniformity and stability. This was accomplished with T4A. In addition, a further gain in performance was obtained by using a screen grid of higher τ than before (approaching 80%) and by reducing grid spacing, when cold, below the original 1.5mm.

Further grid work was carried out at Culham in 1974 to determine the beam profiles produced by the use of accel grids compensated to differing extents. Some of the results are shown in Fig.10; these data, taken together with life-testing information, enabled an optimum degree of compensation to be chosen for subsequent thrusters.

Four of the five T4 thrusters were converted by Culham to T4A standard. The one originally investigated at Culham has continued to be used for development work. For instance, it was found possible to achieve an exceptionally flat plasma density distribution at the screen grid (Fig.23, curve c), and the position and operating conditions of a hollow cathode neutraliser and the physics of the neutralisation process were studied. It has been established that full neutralisation can be achieved and that conditions in space can be reasonably well simulated with a completely floating test system; the thruster, target and cryogenic shrouds must all be isolated from earth if beam studies

are to be representative of the space situation. Other recent work has included the measurement of the doubly charged ion content of the beam.

A second T4A thruster was retained by Culham and was installed in the Laboratory's horizontal test facility late in 1974, while the first thruster was transferred to the vertical life-test facility commissioned in 1975. This second thruster, which was fitted with grids having hexagonal holes, a screen grid having $\tau = 76\%$, a large orifice cathode[10], and production isolators[28], performed very well. It was also equipped with a neutraliser closely resembling later designs (Fig.9), which also behaved encouragingly. This thruster was used mainly by MSDS Ltd. for thruster/pcu integration work (section 2.1.6), although it has recently, in early 1976, been employed for beam and neutralisation studies.

The third T4 thruster was used by the RAE for thermal balance work, and its performance was thoroughly assessed over a very wide range to provide data for the development of the thruster simulator (section 2.1.12). Early in 1974, control experiments were performed using this thruster[38], with very satisfactory results. In particular, cross-coupling between the discharge chamber control loops did not cause instability. Other experiments performed before the conversion to T4A standard in mid-1974 included a series of tests of grids having hexagonal holes. In fact, all subsequent operation has been done using such grids, which have proved satisfactory.

After conversion, the third thruster was fitted with the latest versions of the cathode/isolator/vaporiser assembly, the main flow isolator/vaporiser assembly, and the neutraliser assembly, similar to those shown in Figs.4, 6 and 9. It was used by MSDS Ltd. for extending the earlier pcu integration study, and by the RAE for further thermal and starting sequence investigations. Additional control work and a study of the throttling range available (section 1.5.11) were also undertaken.

The fourth thruster made by Culham was tested extensively as a T4A but with grids having hexagonal holes, then passed to the Fulmer Research Institute early in 1974 for life-testing. Fulmer checked its performance again, and found that the values obtained corresponded closely with the data provided by Culham (Fig.43), confirming that the two organisations had comparable measurement standards and that the thruster had not deteriorated appreciably. The subsequent life-testing is covered in section 2.2.

More recently, in 1976, this thruster has been used by the FRI in the development of one of the probes required by Culham for future cyclic life-testing of thrusters.

It should be mentioned that Culham has manufactured two more T4A thrusters, to the most rigorous standards yet, for the Comsat cyclic life-test. These have the latest components and very careful control has been exercised at all stages of construction.

The testing programme for the T5 series of thrusters has just commenced at the time of writing, the first three models having been manufactured by the RAE. Initial experience, in the RAE, is promising, in that the slight changes introduced to the magnetic circuit have not reduced the performance from that achieved by T4A in any way; indeed, a significant increase has been observed. Section 3 discusses the future programme using T5 thrusters in some detail.

Finally, in view of the concern being expressed in some quarters regarding the inadvisability of using mercury in certain applications, it being an unpleasant air and water pollutant, a small effort is being devoted to the examination of the performance and behaviour of a T4A thruster when using xenon[67] as a propellant. This work is being undertaken by Bristol University, although it should be emphasised here that there is no concern that atmospheric pollution will be a problem when ion thrusters are used in the nssk role.

2.1.4 Thruster life-testing

Ion thruster operating experience in the UK goes back to 1968, and four establishments and 12 separate thrusters have so far been involved (Fig.39). Up to early 1976, four formal life-tests totalling 4000 hours had been included in the project; to this must be added the many thousands of hours accumulated during development testing.

As mentioned in section 2.1.1, the first life-test was of a T2 thruster at the RAE in 1972. It totalled 1700 hours, with 177 starts, and included a hollow cathode neutraliser. Degradation of performance was not severe[55] and no phenomena were observed which suggested that this or later thrusters could not achieve the required lifetime.

The remaining three tests were carried out by the Fulmer Research Institute, commencing in May 1974. A single T4A thruster supplied by Culham was employed for all three, but the grids and feed system components were changed between

tests to investigate any differences that might exist between their long-term performances. Thus the maximum test duration of any one set of these components was limited to about 1000 hours, whereas the discharge chamber, which was not disturbed in any way between tests, was subjected to about 2300 hours. Throughout these long runs, no failures occurred and performance remained at a high level. Examination of the various components of the thruster after each test indicated that none of the possible failure modes listed in section 1.5.13 are likely to be seriously life-limiting factors in the context of typical nssk missions. More detail is given on this topic in section 2.2.

2.1.5 Comsat cyclic life-test

In view of ESA's apparent lack of interest in electric propulsion at the time, a policy decision was taken early in 1975 to concentrate most of the UK ion thruster work in that year on preparing for a possible contract from the Comsat Corp for a 4000 hour cyclic life test, involving some 1300 starts, on a T4A thruster. The Culham Laboratory was the prime bidder in this exercise, with help from the RAE and the Fulmer Research Institute. A similar life test already formed part of the UK's national ion thruster development programme, and it was obviously advantageous to do this in conjunction with Comsat, if possible. It was learnt that the bid was technically successful and Contract negotiations were also concluded successfully, but the contract was not placed subsequently due to funding cuts. The planned test, or a similar one, should, therefore, still form part of the UK's future thruster development programme.

The Comsat RFP[15] specified that any thrusters proposed for the test should be capable of performing the nssk mission on a 1000kg satellite over a ten year period, when thrusting at 30^{o} to the north-south axis of the spacecraft. A large thrust was stated to be preferable to a small one, and battery operation was to be assumed; the maximum energy available per thrusting period was given as 1900W h. Bidders were asked to suggest how their candidate thrusters might be employed to accomplish this mission with good reliability. The bid prepared by Culham, with RAE assistance, suggested the use of four 10mN thrusters. It was claimed that this scheme provides an optimum compromise between reliability, complexity and mass. Assuming no failures, each thruster would then need to operate, on average, once every two days for a time of three hours. In the complete mission, it would run for a total of 4113 hours, with 1375 starts. To demonstrate an appreciable excess capability so that an allowance can be made for failures, Culham proposed to operate for 1500 cycles and 4500 hours.

Of the many aims of this test, two are of particular importance to the future application of ion thrusters to nssk missions. The first is obviously the demonstration that the chosen thruster can operate for the required time, without significant degradation of performance. Life-testing already achieved in both the UK[31] and USA[53] indicates that this is entirely feasible.

Perhaps more important is the need to demonstrate to spacecraft designers that ion thrusters will not so contaminate solar arrays and thermal control surfaces that the entire mission is ruined. In this respect, the Culham life-test represents the most advanced project so far conceived in this area. The instrumentation installed in the new Culham test facility (section 2.4.5) is so comprehensive that almost all material emitted from the thruster or sputtered from its structure can be analysed as regards its mass, charge, energy and direction. In addition, the design of the facility ensures that operation is under conditions resembling those found in space as closely as possible.

Commencing early in 1975, a great deal of effort was devoted to the design and construction of the many probes and detectors needed for this test and to the modification of the test facility to enable the thruster to be operated safely in a cyclic mode completely automatically, with appropriate comprehensive data acquisition. The whole facility is under overall computer control, via a CAMAC system, although the actual cyclic operation of the thruster is carried out by the electromechanical sequencer developed by the RAE (section 1.7.2).

As well as occupying almost the whole of Culham's efforts, considerable support from the RAE, Mullard Ltd. and Fulmer has been necessary in the preparations for this test. The RAE has carried out a study of thruster starting characteristics, including thermal behaviour, and has been responsible for supplying the sequencer, thermal flowmeters and some thruster components. Fulmer has been active in probe development and Mullard has provided the remainder of the feed system components required for the two T4A thrusters constructed for the test.

2.1.6 The power conditioning unit

From the beginning of the project in 1967, it was realised that pcu development would have to await the acquisition of detailed knowledge of thruster characteristics and electrical parameters. Nevertheless, during 1968

and 1969 work was carried out at the RAE on advanced forms of modular power supplies[12], and one of the beam supplies produced was used in the T2 life-test in 1972, with good results. In the next year, a pwm cathode heater supply successfully thermally cycled a cathode 7000 times.

There thus existed a reasonable amount of background knowledge when MSDS Ltd. commenced the development of a complete 'breadboard' pcu[13] in April 1973. The design and construction of this system went remarkably smoothly, and was completed in August 1974. Details of its main features are described in section 1.3.

The next phase of the work, which commenced almost immediately, was to operate the pcu with a T4A thruster. This was done initially at Culham, so that MSDS would have rapid access at all times to plasma physics expertise. In addition, it was desirable to use a test facility (section 2.4.4) allowing the thruster, target and cryoshrouds to be electrically floating, to enable the performance of the part of the pcu supplying the neutraliser system to be properly evaluated. A move to the RAE became necessary in May 1975, due to the need to carry out neutralisation studies in this test facility at Culham. The work is continuing at the RAE, although activity between mid-1975 and early 1976 was severely restricted, owing to the concentration of funding on preparations for the Comsat life-test.

During this programme of work at both Culham and RAE it was found that the individual pcu modules operated the thruster in a reasonably satisfactory manner. Few adverse interactions were observed and noise levels were generally acceptable, although a few modules proved unsatisfactory in this respect. In addition, the complete pcu was able to power the thruster, and the starting sequencer also functioned as intended. The major defect discovered concerned the turn-on of the beam supply, but this was largely due to an unavoidable deficiency in the original specification for the pcu project. Due to inadequate information at the time of writing the specification, the overload current capability required of the beam supply at switch-on was tentatively put at 20%. This was found to be too low. As described in section 3, the redesign needed to correct this point and to deal with other similar problems is now being undertaken by MSDS; this updating includes the use of a microprocessor for sequencing and control.

2.1.7 Hollow cathode development

As shown in Fig.39, most of the hollow cathode work has been carried out by the RAE and Mullard Ltd., although Culham has contributed to the technology and life-testing. In general, the RAE has concentrated on basic physics and manufacturing technology, whereas Mullard has been largely concerned with manufacturing technology and life-testing.

Work commenced at the RAE at the end of 1967 on cathodes resembling those used in the SERT II programme. Some were initially procured from GEC Ltd. and others were made later by the RAE (Fig.44). The basic aim was to gain an understanding of the physical processes important to the operation of these cathodes and, in particular, to evolve a theory of the relevant electron emission mechanism. Consequently, the first phase of the work consisted of an extensive study of current-voltage characteristics, when operated in diode discharge systems[29]. The influences exerted by many different parameters were established and progress was made in the search to identify those features most important in the attempts being made to achieve higher performance and longer life. By late 1969, durabilities of hundreds of hours had been realised and, early in 1970, a dual-part electron emission theory had been formulated[29]; this included field-enhanced thermionic emission and secondary emission by impact of metastable mercury atoms with the internal walls of the cathode. Subsequently, additional work in 1971 and 1972 with both internal and external Langmuir probes and with specially-shaped cathode orifices has tended to confirm this theory[10]. Additional corroboration has come from an optical investigation in the USA of the inside of an operating cathode[68].

Other work going on in parallel at the RAE included studies of discharge initiation[10], using both the keeper electrode and internal electrodes; no other similar studies have ever been reported, as far as is known. The starting tests using the keeper showed that initiation is a random process at a given flow rate and cathode temperature, unless the applied voltage exceeds a reasonably well-defined value. This value is reduced as these two parameters are increased. The distribution of barium was found to be an important factor.

In 1972, a comprehensive study was carried out concerning the use of cathodes under conditions appropriate to the neutraliser application[33]. It was established that the type of cathode then available would operate at exceptionally low flow rates and temperatures, down to 0.004mg/s and 300°C, in the neutraliser

mode. Under these conditions, the keeper discharge is the controlling factor, electrons merely diffusing to an anode or the ion beam under the influence of the applied electric field. The very great influence of orifice diameter was also established.

In 1971, cathode life-testing in diode systems also commenced in the RAE and, to date, many long tests have been carried out, exceeding 5000 hours duration in some cases[20,35]. These tests, in conjunction with those carried out by Mullard, have shown that the design and operating conditions of the barium dispenser are crucial to long life, provided that the vacuum system employed has an adequately low background pressure. It has also been determined that the results obtained are significantly dependent on orifice size. Up to 1975, all such tests were run under steady-state conditions, but the latest in the series is cyclic, the cathode being on for three hours and off for slightly less than one hour. Many cyclic tests of cathode heaters have been performed between 1972 and the present, up to 15000 rapid heating cycles having been recorded with a single heater.

In 1973 and 1974, many of the investigations mentioned above were repeated using porous tungsten barium dispensers[35,37]. In general, it was shown that they did not perform quite as well as the previously employed rolled-foil dispensers, particularly in the neutraliser application, but that their advantages of robustness and durability were sufficiently great for them to be adopted for future thrusters. Subsequently, improvements in manufacturing technology[36] enabled considerable performance gains to be made, and all cathodes now tested use this type of dispenser.

The involvement of Mullard Ltd. began early in 1968 with a study of the discharge characteristics of cathodes of the SERT II type, and of the appropriate manufacturing technology. As regards the technology, the early effort was devoted to the following major areas, where problems were anticipated (Fig.44):

(a) drilling accurate, parallel-sided holes in the tungsten tips,

(b) welding tungsten tips to tantalum or molybdenum bodies,

(c) producing mercury-resistant brazes between isolators and cathode bodies,

(d) protecting the tantalum bodies, if used, from attack by the heater encapsulant,

(e) obtaining suitable heater wire and an appropriate encapsulant,

(f) manufacturing the dispenser.

These and other points have been resolved, and the remaining work is mainly concerned with quality control and with life-testing.

From late 1970 to early 1973, the emphasis of the Mullard studies was shifted gradually to porous dispenser cathodes and, as in the RAE, all present work is now devoted to them. Another gradual shift of emphasis, from basic physical investigations to life-testing, began somewhat earlier, in 1969, with a series of short term, high current tests to determine the influence of orifice size on erosion (Fig.32). This was followed by a simultaneous test of eight cathodes, also at a high current of 3A. All eight lasted 600 hours without failure, and some had been run to 1700 hours by the end of 1970. Life-testing recommenced early in 1971 and, on this occasion, the eight cathodes included some operated under neutraliser conditions. By the end of the year, up to 1800 hours had been achieved, despite severe problems with the test facility, and one cathode, running at 3A, reached 2500 hours. Also in 1971, cyclic tests were performed on several cathodes, and up to 840 starts were recorded[58].

Apart from a continuing effort on the development of manufacturing technology, the analysis of life-tested or failed cathodes[36], and the production of components for fitting to various thrusters, the major effort by Mullard from September 1972 has been to develop the integrated cathode/isolator/vaporiser assembly depicted in Fig.4, and to apply the same technology, from the beginning of 1975, to the production of other flow system components (Figs.6 and 9). The basic design work, however, was done by the RAE, commencing in mid-1970, the aim being to have a reasonably well proven integrated assembly available by the time the T4 thrusters were ready for operation. As well as carrying out design work, the RAE was responsible for all the initial development of the radiation shield system and of the bifilar cathode heater[28], together with the assessment of performance and thermal behaviour and the issue of a specification. All later development was carried out by Mullard using, in many areas, production techniques evolved specially for this task. The work included, at various stages, performance testing, the evaluation of thermal characteristics and of vibration resistance, and extensive thermal cycling of heaters. The programme culminated in a series of formal vibration tests and a severe 2000 cycle thermal test, the latter including a peak temperature of 1300°C and a very rapid heat up time of less than five minutes.

In parallel with the latter part of this development exercise, a sophisticated cathode life-test apparatus was designed by Mullard and built under subcontract by Edwards High Vacuum Ltd. The next stage in the development of the integrated assembly is to use this apparatus for the cyclic life-test of a number of assemblies to 5000 hours, with 1700 starts. Although the apparatus will cater for eight integrated assemblies, only four will be tested, the other four experimental stations being occupied by neutralisers (Fig.9), which are constructed using the same technology. A simplified version of the electromagnetic sequencer is to be used to automatically start and stop the discharges (section 1.7.2).

It should finally be mentioned that, from 1968 to September 1975, a low level of effort was funded at Liverpool University which was aimed at establishing the exact form of the left-hand limb of the Paschen curve for mercury vapour (Fig.45) and at evolving a theory to explain the re-entrant characteristic observed in that region[26,27]. This programme of work was extremely successful.

2.1.8 Isolators

Isolator development work, which was undertaken solely by the RAE, was commenced in late 1968 with the change, in the T1 test programme, from a thermionic to a hollow cathode. The additional flow impedance caused by the hollow cathode orifice raised the pressure in the feed system so that an empty tube[64] might break down electrically at some stage during a thruster operating cycle (Fig.45). The approach to solving this problem was to fill the tube with a porous insulator[25] which, it was thought, would inhibit breakdown. Initially, the porous material was simulated by glass and alumina spheres covering a range of diameters, and, as seen in Fig.7, the results were very successful.

Early in 1970 a contract was placed on Anderman and Ryder Ltd. for the development of techniques for manufacturing these isolators entirely from alumina. This took less than one year, and very good results were achieved (section 1.2.4). In parallel, physical investigations continued at the RAE, where it was established, by measuring internal electric fields by means of wire probes, that the performance of an isolator depends on the exact form of this field. The best results were obtained with equal fields at both ends; these can be produced if necessary by appropriately biassing an auxiliary external electrode at the centre of the tube.

It was also found that the breakdown voltage of an isolator under given conditions was reduced significantly by UV radiation or electrons from an operating cathode attached to it. It was shown that this could be prevented by interposing a porous stainless steel or tungsten screen between the two devices.

In 1973, Anderman and Ryder reduced the diameter of production isolators further, making them more suitable for use in the integrated cathode/isolator/vaporiser assembly being developed by Mullard. It was also found possible to reduce the pore size in the porous structure, raising the minimum breakdown voltage.

There have, to date, been three life-tests of isolators, and all have given satisfactory results. The first was in the 1700 hour T2 life-test (section 2.1.1), the second was a 2800 hour diode test[20], and the third was in a 1000 hour T4A test at Fulmer (section 2.2). The diode test, which was carried out in the RAE in 1974, was particularly significant, as it revealed the importance of using adequate sputter shielding and of exercising care in causing diagnostic breakdowns.

2.1.9 Vaporisers

The development of this component has been undertaken solely by the RAE, although much manufacturing effort has been funded in Industry.

The first vaporiser produced, for the T1 thruster[64], was large and not very successful, but it was replaced, by mid-1968, by the type described in section 1.2.5, and the design has remained essentially unaltered since then. Although initially following American concepts, the later design[24] differed substantially from those found in the USA, in that it employed a small, thin porous plug, an alumina-encapsulated heater downstream of the plug, and almost complete thermal decoupling from the components connected to it. These features provided considerable benefits, including small size and low power consumption, and several other development teams have now adopted them.

The basic development was completed in mid-1969, although gradual improvements to detail design and quality control occurred afterwards. A rather larger change was necessary in 1971 to improve the heater terminations and to raise the heater resistance to the value required by the pcu.

As regards life-testing, this is done whenever a thruster or cathode is life-tested; the maximum duration achieved so far in this way is 13500 hours.

In addition, two formal life-tests have been carried out at the RAE, both of a group of three vaporisers, in 1972 and 1975. The first was a steady-state test, the second was cyclic.

2.1.10 Tanks

Tank development commenced in 1969 with the design, construction and comparative testing of a spherical bag tank and its bellows equivalent[46] (section 1.4.1). The bellows tank was selected for later use, but development was not resumed until late in 1974, when a 5kg device of a higher expulsion efficiency and lower mass was designed. This is now being tested, following construction by Sealol Ltd., and an accelerated life-test of the effect of liquid mercury on the bellows material and welds[69,70] is also in progress.

2.1.11 Flowmeter

Several mercury flowmeters have been worked on in the RAE at various times, but, of these, only the thermal flowmeter[11] (section 1.7.3) is being developed to the state where it could be flight qualified.

The basic concept of the thermal flowmeter was evolved in 1969 and development has continued slowly to the present day; this has never been an urgent item because the nssk mission does not require its use, although it has valuable laboratory applications. The reason for its acceptance for further development, while the other methods were rejected, included its small size, simplicity, absence of moving parts, low power consumption and complete independence from all other system components. As already mentioned, the laboratory device is at present being further developed by Mullard Ltd., to improve its accuracy and reproducibility, whilst reducing its size and mass. It should then be capable of space qualification, together with its associated electronics, should this further step be required.

Laboratory flowmeters are currently fitted to two test facilities, these being the larger ones at both RAE and Culham (sections 2.4.1 and 2.4.5). They should prove particularly useful in life-testing, because they can provide a continuous record of flow rate.

2.1.12 Thruster simulator

It was realised in 1972 that a simulation device would eventually be needed to check-out the pcu, it not being possible to operate the thruster in the actual spacecraft prior to launch. In addition, such a device would be

useful in pcu development if it could properly simulate the electrical loads provided by the thruster over a wide range of operating conditions. It was envisaged that a simulator could be produced using a complex arrangement of diode function generators to represent individual thruster performance characteristics.

The original design was based on the measured performance data of the T2 thruster and, late in 1973, it was established that a realistic simulation could be achieved. Consequently, in 1974 the design was modified to reproduce the characteristics of a T4 thruster, with excellent results[59]. The next stage of the work is to update the device to T4A standard and to include those features which have not so far been incorporated into the design, such as the neutraliser system and the hollow cathode heater characteristics.

2.2 Details of life-testing achieved

Throughout the development programme leading to the design and production of the T4A thruster, a considerable amount of life-testing has been carried out, both of thrusters and of components. In particular, three long-duration tests have been completed at the Fulmer RI, using the same T4A thruster. In addition, an aggregate of many hundreds of hours of operation has been accumulated at the RAE and at Culham.

2.2.1 Thruster life-testing

Life-testing at the FRI is carried out in a 0.9m diameter vacuum facility having a solid mercury target (section 2.4.3)[66]. The performance of the facility and of the instrumentation has been investigated in depth. It has been shown, by employing several methods, including an oscillating cryogenically-cooled quartz crystal detector, that the back-sputtering rate of mercury atoms from the target is very low. At the grids of the thruster, it is typically $6 \times 10^{-9} g/cm^2/s$ for $I_B = 200mA$ and thruster potential $V_T = 1.8kV$. This represents 0.5% of the neutral efflux from the thruster with $\eta_m = 80\%$, and 1% of the efflux for $\eta_m = 90\%$. The equivalent values are lower with $I_B = 167mA$ and $V_T = 940V$. Test facilities with targets made of other metals appear to suffer from higher back-sputtering rates[6]; this problem is made more serious by the failure of such metals to evaporate from thruster surfaces on which they are deposited, thus fundamentally affecting the data obtained from a life-test.

It has been shown that efficient neutralisation of the ion beam is essential if meaningful life-tests of grids are to be carried out; target or residual gas

neutralisation are totally inadequate. For example, the peak arrival rate of material sputtered from a thruster was measured at various positions near the grids by a collimated deposition technique. Although turning on the neutraliser caused little measurable change to the thruster characteristics or to the beam shape, it reduced the arrival rate of sputtered molybdenum at a point about 20cm from the centre of the grids and at angles of between 50 and 85^{o} to the thruster axis by a factor of about 300. Similarly, the arrival rate of stainless steel sputtered from the earth screen was reduced by a factor of about 50. A theory explaining this effect has been evolved[30].

Life-testing of the T4A thruster at FRI has currently exceeded 2300 hours, with no thruster failures. For the first 200 hours, the thruster was operated with uncompensated grids with hexagonal holes and $\tau = 76\%$. Operation was entirely satisfactory, although the measured rate of deposition of material sputtered from the accel grid was higher than found with grid sets tested later, possibly due to ion optical aberrations in the hexagonal system.

The thruster was subsequently fitted with compensated grids with circular holes and 1% strain, and operation with these[31] exceeded 1000 hours. Apart from the normal charge-exchange erosion, examination showed that some direct impingement had occurred in the peripheral holes, confirming an initial prediction that 1% strain might be slightly too great. The rate of deposition of sputtered molybdenum was again measured, using suitably collimated and positioned monitors. The results at 500 and 1050 hours, shown in Fig.46, indicated that the sputtering rate fell as the test progressed, thus confirming the significance of the accel grid current data, which decreased rapidly to the normal value of $\leq$0.4mA during the early part of the test. The measured deposition rate 20cm from the centre of the grids was, between 500 and 1050 hours, 5×10^{-12}g cm^{-2}s^{-1}.

After 1050 hours, the grids were examined in detail. The etch pits at the centre of the accel grid were 0.1mm deep, and the total weight loss was 0.2g. Using a linear extrapolation from either value, with the assumption that all sputtering occurred from the central 5cm diameter of the grid, pessimistic life predictions of about 30000 hours were obtained. There is thus little doubt that the grids will last for the duration of most missions of interest.

During the 1050 hour test, all thruster parameters, including the ion beam profile, were monitored regularly. No degradation of any kind was apparent. In particular, V_k remained very steady at 11.1 ± 0.25V, indicating that cathode

performance remained good throughout the test. Full thruster performance checks were carried out on four occasions, giving the results presented in Table 8.

Table 8

Performance data during first 1000 hour life-test

ΔV	Values of η_m (%)				eV/ion			
	Hours				Hours			
	382	500	740	1016	382	500	740	1016
22	78	78	75	79	250	239	240	231
27	86	87	84	88	258	246	247	237
29*	90	89	87	90	260	251	250	243

* Normal operating value

The consistently high values of η_m were confirmed by weighing the propellant consumed; this gave a mean for the whole test of $\eta_m = 90 \pm 1\%$.

In view of the minor amount of direct impingement experienced early in the test, 0.5% compensated grids were fitted for the next 1000 hour run. The opportunity was also taken to fit an improved cathode, together with fully integrated vaporisers and isolators, as depicted in Figs.4 and 6. In addition, a hollow cathode neutraliser assembly was included. No other parts of the thruster were touched; in particular, no components were cleaned in any way or given any surface treatment.

The second test continued smoothly under manual control to its planned conclusion at 1045 hours, with 11 restarts. Three restarts were deliberate, the thruster being exposed to air on these occasions in order to examine its condition. The remaining starts were due to test facility malfunctions. At 630 hours, the power supply connected to the hollow cathode isolator failed and applied its full uncontrolled voltage of above 50V to the heater, causing it to burn out. This is not classed as a thruster failure, and it did not effect the test as the isolator heaters are not normally needed during steady operation.

As previously, full records were taken of most parameters throughout the test. As can be seen from those illustrated in Fig.47 there were considerable fluctuations due to the use of primitive control, but the thruster remained completely stable at all times and efficiency was consistently very high.

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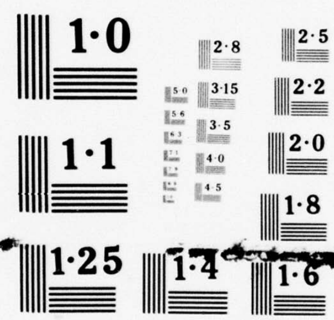

NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

A major part of the fluctuations was due to laboratory temperature changes, which effected most of the power supplies to some extent and considerably influenced the vaporiser temperature controllers. This strongly confirms the need to use active control loops. The only sign of degradation was a slow rise of V_k from about 10.5V to 11.5V, and it is likely that this was due mainly to the rapid evolution of the barium contained in the dispenser adjacent to the hot cathode tip. Diode tests suggest that this should be followed by a long period in which V_k remains virtually constant.

Mean values of various parameters throughout the test are given below, together with their standard deviations:

Beam current	0.168 ± 0.007A
Discharge voltage	39.7 ± 1.6V
Keeper potential	11.1 ± 0.2V
Keeper current	0.621 ± 0.014A
Accel grid current	0.5 ± 0.06mA
eV/ion	236.5 ± 15
Body temperature	130 ± 4°C
Room temperature	18.1 ± 2.6°C
Neutraliser keeper current	0.26 ± 0.04A
Accel grid voltage	375V
Total mass flow rate $\dot{m}_T$	0.390 ± 0.003mg/s
Mass utilisation efficiency	89.5 ± 1%

It should be noted that the standard deviations associated with the values of $\dot{m}_T$ and η_m are probably larger than necessary, because average flow rates were assessed very accurately by weighing the propellant consumed, and the beam current was integrated over time to deduce the mean value of η_m.

The beam profile was checked with an ion probe at intervals, and no changes were detected. Similarly, isolator leakage currents were measured at suitable times and the small increases observed were explainable by residual external deposition of material[20]. The use of an opaque earth screen should eliminate this.

Throughout the test, an electronic counter was used to detect inter-grid transient currents; this device could be adjusted to respond to current levels and pulse widths exceeding set limits. However, no transients were detected of a magnitude or duration likely to cause grid damage[71], in agreement with

observations made during thousands of hours of development testing. This result confirms that the thruster is exceptionally stable and docile in operation.

At the conclusion of the test, the thruster was examined in detail. The grids were in excellent condition, but there was evidence of an initial misalignment, so the expected decrease of sputtering caused by direct impingement was not fully realised. Nevertheless, the weight loss of the accel grid was 0.14g rather than the previous 0.2g. The erosion pits were approximately as deep as before, the maximum being 0.1mm with a mean of 0.08mm. These pits first appeared at 100 hours and were 0.05 to 0.07mm deep at 700 hours. The mass removed from the erosion pits, estimated at 0.06g, compared favourably with estimates based on sputtering by charge-exchange ions. The life expectancy of the accel grid was calculated to be similar to that deduced from the first 1000 hour test, that is about 30000 hours or more.

All insulators were in excellent condition, and showed very high resistances when tested at 1kV. Both isolators were measured to be 500MΩ, the grid insulators and the neutraliser keeper insulator were 10^3MΩ, the neutraliser flow insulator was 80MΩ, and the main keeper insulators were 10^4MΩ.

Both cathodes were in good condition. The external diameter of the orifice of the discharge chamber cathode had increased slightly, from 0.30 to 0.32mm, and a tungsten deposit, presumably sputtered from the cathode tip, was found on a monitor surface placed on the thruster backplate within the inner polepiece.

At the completion of this second 1000 hour test, the discharge chamber had been operated for 2315 hours without being disturbed. In this time, the anode gained 0.23g, but showed no signs of flaking of the deposits on its surface, despite many exposures to air. However, at 1971 hours, slight flaking had become apparent on the discharge chamber wall upstream and downstream of the anode. This was not regarded as serious because the typical flake size was 0.25mm - the word 'dust' would be more appropriate. An analysis showed that the material was mainly iron, with less than 5% molybdenum, so the source may have been the inner polepiece, which lost 0.12g. The baffle disc lost only 13mg in these 2315 hours, indicating that the sputtering problem is far from severe in this thruster.

The monitors used to measure the rate of deposition of material sputtered from the accel grid indicated, in the second 1000 hour test, the type of directional effect that might be expected from misaligned grids. The monitors viewing

the parts of the holes most likely to suffer direct ion impingement collected far more molybdenum than those viewing at 90^o. In fact, the amount collected by the latter agreed closely with the values shown in Fig.46 for the first test, as should be the case for charge-exchange sputtering only.

Using the data in Fig.46, the total deposition in 5000 hours of operation at a distance of 1m from the thruster has been calculated. The results are shown in Fig.48, together with the transmittance through the deposited layers, which were evaluated using coefficients given in Ref.72. The 1m distance was selected as being representative of the closest approach of any part of a solar array to a thruster. The thickest deposit occurs at an angle of $35-40^o$ to the plane of the grids, and it is well below 50Å. The transmittance for this worst case is about 0.6, which is not unreasonable for the end of life condition, considering that the value will fall off very rapidly with distance. To show this, equivalent data for 1.5 and 2.0m are also plotted, and it will be seen that, in the latter case, the end of life transmittance is virtually 100% over all angles.

2.2.2 Component life-testing

During development of the various important thruster components, a considerable amount of cathode, vaporiser and isolator life-testing has been carried out, mainly in small vacuum facilities specifically prepared for the purpose. Results have been impressive, cathodes having exceeded 5000 hours [35], vaporisers 13000 hours, and isolators 2500 hours [20]. In addition, cathodes have been started from cold up to 840 times[58] and cathode heaters have been thermally cycled up to 15000 times without failure. Table 9 summarises experience to date.

Although these tests have been performed on a variety of components at various stages of their development, confidence has been gained in the ability of the technology employed to meet the requirements of most currently proposed missions. It has, for example, been shown that cathode orifice erosion can be reduced to a negligible amount by correct choice of diameter[34], ceramic to metal brazes and heater coatings can withstand repetitive thermal cycling if materials are selected and applied carefully, and the rate of use of the available barium in a cathode can be adjusted to mission requirements by control of operating parameters. In addition, the rate of performance degradation observed due to gradual barium depletion is sufficiently low for the thruster control system to take it into account.

Table 9

Component life-test experience

Component	Time or number of cycles	No. of components
Cathodes	4600-5300 hours	4
Cathodes	2500-3000 hours	3
Cathodes	900-2000 hours	16
Neutralisers	500-5000 hours	7
Cathode heaters	15000 thermal cycles	1
Cathode heaters	4000-7000 thermal cycles	2
Cathode heaters	2000 rapid thermal cycles	3
Isolators	1000-2600 hours	8
Vaporisers	1000-13000 hours	33
Integrated assy.	2000 thermal cycles	1

Although a great deal of cathode heater thermal cycling has been done, one notable gap in the life-testing accomplished to date is cyclic operation with a representative discharge. However, tests of this kind are now being performed at the RAE and an eight-cathode test is due to be started in Industry shortly. Results obtained so far, when taken in conjunction with past experience[58], suggest that cycling performance should be entirely adequate, but this remains to be properly demonstrated, as indicated in section 3.

2.3 Remaining problem areas

As already mentioned in the discussion of life-limiting factors (section 1.5.13), no serious problems of a difficult nature, which require large steps into unknown areas for their solution, can be foreseen at present. Most of the obstacles encountered during development have already been surmounted by advancing design or technology, or life-tests have demonstrated that they are not as significant as thought at first. An example of the former case is the problem of accel grid erosion, which was overcome by general improvements to the performance of the thruster. In the latter category can be included cathode orifice erosion, which was originally considered very serious, but which experience has shown to be unimportant for the nssk mission.

At the present time, it is true to say that no technical problems of comparable severity to that presented by the accel grid erosion on SERT II can be

foreseen. Most of the remaining work described in section 3 is of a fairly routine and well-defined nature which, although requiring funds and other resources, is not likely to give rise to serious technical difficulties.

It should of course be recognised that minor difficulties can occur almost continually in a large development programme, such as that required for an ion thruster system. At any time there are obviously innumerable detail aspects which need some investigation. To attempt to describe these as they appear at present would not only be confusing but possibly even misleading, as some of them may be cleared up before this report is even produced, while new ones are likely to occur. Accordingly, they have not been included in this section, but a number have been mentioned previously in connection with various parts of the thruster system.

It is perhaps helpful to list those areas where significant work is required, and this has been done in the remainder of this section. Two major areas are fundamental to the acceptance of the whole ion thruster system and are applicable to each part of it, so they are referred to first. They are:

(a) Extensive cyclic life-testing, particularly of the thruster, its critical components, and the pcu. This activity dominates much of the future programme and is perhaps the one most likely to raise significant problems.

(b) Qualification tests. These are essential prior to the acceptance of the system for flight, and are also prominent in the programme discussed in section 3.

The other areas of major activity are listed under the following headings.

2.3.1 The thruster

(a) Complete the optimisation of the neutraliser mounting position on the thruster and study the neutralisation process.

(b) Finalize mounting arrangements for the thruster, together with its propellant stop valves, plugs and sockets, to suit specific satellite requirements.

(c) Finalize thermal balance arrangements to suit specific satellite requirements.

(d) Update the mechanical design of the thruster and prove its integrity under vibration.

(e) Investigate the addition of a redundant cathode to the thruster (for the operational flight only).

(f) Store and subsequently retest cathodes and flow system components after they have been operated on a thruster. This is to establish the integrity of the system following a storage period which is preceded by an acceptance test.

(g) Check in detail the characteristics of the exhaust plume from the finalized thruster, to confirm the suitability of the proposed installation arrangements in a satellite.

(h) Examine the electromagnetic radiation produced by the thruster, to establish that it does not interfere with the remainder of a spacecraft.

2.3.2 The power conditioning unit

(a) Complete updating of the breadboard pcu, including the sequencer, to meet the latest thruster operating requirements. Integrate the updated pcu with a thruster and prove the closed loop control system.

(b) Carry out a detailed reliability study of the updated pcu and incorporate appropriate passive and active redundancy in the design so as to achieve the desired overall reliability value.

(c) Package the complete pcu, including sequencer and control logic, in a form suitable for satellite installation. Check the operation of the electronics package on a thruster.

(d) Ascertain that the packaged pcu is compatible with the specified electromagnetic interference limits of the spacecraft.

(e) Complete development of the thruster simulator and integrate it into the system check-out equipment when this is designed and built.

2.3.3 The propellant system

(a) Test and, if necessary, update the latest tank design.

(b) Manufacture and prove the structural integrity of a batch of tanks.

(c) Develop a set of latching mercury stop valves.

2.4 Test facilities available in the UK

The UK possesses a comprehensive range of ion thruster test facilities, which are adequate for the development programme discussed in section 3. These

facilities include two well-instrumented test chambers at the Culham Laboratory; the largest of these is probably the best in the world for investigating the characteristics of the exhause plume from a thruster. In support of these major facilities, which are dedicated to mercury ion thruster work, there are also available numerous smaller test chambers used for component development and life-testing. These are mentioned only briefly below.

In addition to dedicated facilities, the UK also possesses others which are available for general spacecraft development and testing. However, thruster operation in these is not possible, because contamination by mercury must be avoided. Consequently, they may be employed only for environmental testing.

The development timescale discussed in section 3 can be met by using UK facilities alone. If, however, an appreciably faster programme is desired, additional test chambers may be needed, depending on the exact programme adopted.

2.4.1 The RAE 1.5m diameter facility

This 3.5m long horizontal chamber, which is shown diagrammatically in Fig.49, was purpose built by Edwards High Vacuum Ltd. from 18/8 stainless steel. It is pumped from below by two Edwards F3605 oil vapour diffusion pumps of 0.9m nominal diameter. Refrigerated chevron baffles are fitted between the pumps and the chamber. No high vacuum valves are fitted. The 0.6m diameter by 0.75m long vacuum lock can be independently pumped by an Edwards E06 oil vapour diffusion pump; it is separated from the main chamber by a gate valve.

The system is manually operated, but remote actuation of all valves, gauges and pumps is provided, coupled with adequate system status indicators. Some safety circuits are provided in critical areas, such as the cooling water supply, to ensure safe automatic shut-down in the event of failure. Without liquid nitrogen cooling, the system is capable of achieving a vacuum of better than 4×10^{-7} torr and, with a 10mN thruster operating, the vacuum lock pressure is approximately 1×10^{-6} torr.

Liquid nitrogen is supplied to the installation from a pressurised 10000 litre tank. The cylindrical walls of the main chamber are lined by three stainless steel double skinned cylindrical cryoshrouds which are kept filled with liquid nitrogen. Adequate strength is provided for the thin walled construction by welded dimples. The nitrogen liquid level is maintained automatically, above each liner independently, by a liquid level sensor which provides the error signal for opening or closing the solenoid operated flow control valves. The vacuum lock has no cryoshrouds.

Titanium was chosen for the 1.2m diameter target to take advantage of its relatively low sputtering yield under mercury ion bombardment[73], and also because the fresh surface layers exposed continually by sputtering act as very effective getters for residual gases in the system. To minimise the amount of sputtered titanium reaching the thruster, the target has a conical shape. It was made by the same constructional technique as were the shrouds, and it is also kept filled with liquid nitrogen.

The facility is equipped with a comprehensive range of laboratory power supplies and electrical measuring instruments. In addition, the power lines to the thruster may be rapidly switched by high voltage reed switches to allow the pcu to be connected during operation, either completely or on a module-by-module basis. This feature has saved a considerable amount of time in pcu/thruster integration studies.

In addition to the visual data displays, digital recording is available from a Dynamco digital data logger. As it accepts earth reference analogue signals, direct current signals at beam supply reference may be transferred to earth reference by optical isolators or by a simple FM circuit with transformer coupling between modulator and demodulator. In addition to a print-out from the data logger, information can be stored on punched tape, which is in a form suitable for use on one of the RAE computers.

2.4.2 The RAE 0.9m diameter facility

This horizontal Via-Vac facility, which is shown in Fig.50, is 1.8m long and has a configuration similar to that of the larger chamber, except that it is pumped from the side. The thruster is housed in a 0.6m diameter by 0.75m long vacuum lock, separated from the main chamber by a gate valve. The two 0.4m diameter oil vapour diffusion pumps achieve an ultimate pressure of 5×10^{-7} torr, and a vacuum lock pressure of 5×10^{-6} torr when the thruster is operating at 10mN. They are equipped with refrigerated baffles and high vacuum valves. Each pump is backed by a smaller diffusion pump, then a rotary pump. The vacuum lock may be separately evacuated, but is not fitted with cryoshrouds.

The chamber is lined with liquid nitrogen cooled stainless steel shrouds similar to those described in section 2.4.1. The titanium target is also of a similar design. They are supplied with liquid nitrogen from a storage tank via a centrifugal pump, which maintains a continual circulation of liquid. This complex system is employed because it was already available, having been installed

prior to the start of the ion thruster project when the chamber was used with different shrouds for thermal tests of spacecraft components.

The power supplies provided for thruster operation are similar to those available in the larger RAE facility. There is, however, no data logging capability and pcu connections are not provided.

2.4.3 The Fulmer 0.9m diameter facility

This vertical facility was purpose-built for ion thruster life-testing, so great care was taken during the design phase to ensure, within the constraints of a reasonable budget, that the test conditions were as realistic as possible. In particular, two major design aims were that the background pressure of atmospheric gases should be in the 10^{-7} torr region and that the thruster should be influenced to the minimum extent by material sputtered from the target. The latter stipulation was met by employing a liquid nitrogen cooled solid mercury target. The calculated backsputtering rate was then sufficiently low for the length of the main chamber to be only 1m, assuming the use of cryopumping for mercury vapour.

A diagram of the facility is shown in Fig.51, from which it will be seen that the thruster under test is mounted in a vacuum lock separated from the main chamber by a 30cm diameter gate valve. When mounted as indicated, the accel grid of a thruster is 1.3m from the target and a beam divergence of 15^{o} can be accommodated before the beam edge impinges on the gate valve. Two 2000 l/s mercury diffusion pumps are fitted to the main chamber, and a third is connected to the vacuum lock. Each pump can be isolated by a high vacuum valve and each has a liquid nitogen cooled cold trap mounted above it. Cylindrical cryoshrouds are provided in both the main chamber and vacuum lock. The target consists of a shallow pool of mercury resting within a liquid nitrogen cooled container. With the thruster operating at 10mN, the pressure around the thruster is about 1×10^{-6} torr.

Fairly extensive diagnostics are provided, including ion probes, a mass spectrometer, and collimated detectors for measuring the rate of arrival of material sputtered from the thruster at a particular angle[31]. A cryogenically cooled quartz crystal mercury vapour monitor is also available.

Reference has already been made to the excellent performance of the facility and to the life-tests so far performed in it (section 2.2.1). In the calibration experiments carried out using a T2 thruster[66] it was shown that the

back-sputtering rate from the target to the thruster is remarkably low. It amounts to only 0.5% of the neutral efflux from the thruster at $\eta_m = 80\%$ and 1% at $\eta_m = 90\%$. It was also shown that proper neutralisation of the ion beam is essential for the acquisition of meaningful grid life-test data.

Laboratory-type thruster power supplies are provided, together with a limited amount of continuous data recording equipment. Extensive safety interlocks have been incorporated into the system to ensure a safe shut-down in the event of a facility failure or if certain thruster parameters go beyond pre-set limits.

2.4.4 The Culham 1m diameter facility

This heavily instrumented 2m long horizontal test facility, shown in Fig.52, has been used for the majority of the plasma physics investigations performed at Culham. The section containing the target is of 1.0m outside diameter, whilst the diameter of the other section, which houses the thruster, is 0.6m. Cryogenically cooled shrouds are provided in both sections, but the target is not cooled because it is divided into electrically isolated annular rings to provide information concerning beam divergence. The chamber is evacuated by two diffusion pumps of 0.15 and 0.23m diameter, and a third pump, with a cold-trap system, is provided to scavenge mercury from the chamber during times when the thruster is not being operated. The ultimate vacuum attainable is about 10^{-7} torr.

The power supply and data acquisition systems are particularly comprehensive and versatile. In addition to the usual laboratory supplies, many others are provided, because all sections of a typical diagnostic thruster require, at times, to be biassed electrically with respect to each other[7]. Similarly, large amounts of information are produced continually by most experiments, so provision is made for automatic data acquisition at both high and low voltage reference, with optional computer processing. The automated system has been extended to include the recording and analysis of Langmuir probe characteristics, which is a laborious task when undertaken manually.

The diagnostic arrangements are particularly comprehensive. As well as the annular target, the cryoshrouds can be biassed electrically; they are also shielded by grids provided to suppress secondary electrons. Several ion beam and Langmuir probes can be inserted into the facility through the flange from which the thruster is mounted. These probes are moved within the ion beam

region or inside the thruster itself by precisely calibrated drives situated outside the facility. By use of these drives, spacial variations of plasma and ion beam parameters may be obtained. Ion gauges are also available for measuring the pressure within a thruster, and a time-of-flight mass spectrometer has been constructed and employed to determine the doubly-charged ion content of the ion beam[8] (Fig.24).

2.4.5 The Culham 1.2m diameter vertical facility

The vacuum chamber, shown in Fig.53, is constructed of stainless steel, and is 1.2m diameter throughout its cylindrical length of 2m. The thruster is suspended from a top plate through which are brought insulated seals for the various electrical leads and mercury feedthroughs, together with diagnostic probe drives. The top plate can be lifted off and then rotated through 90°, thereby bringing the thruster axis to a horizontal attitude for easy servicing. An electrically insulated stainless steel target containing frozen mercury is supported in the dished bottom of the chamber. Two stainless steel cryogenic shrouds are located concentrically within the vacuum chamber; these are also electrically insulated. In addition to the service ports, there are ten diagnostic ports for inserting the numerous probes used in studying the exhaust plume of the thruster.

As indicated in Fig.53, the accel grid of the thruster is situated 1.2m from the target and beam divergence can rise to 21.5° before appreciable ion impingement occurs on the lower shroud. In any case, that shroud is kept permanently covered with mercury during testing, to ensure that only propellant is back-sputtered towards the thruster.

Two Edwards F903 oil diffusion pumps fitted with refrigerated chevron baffles and baffle valves give an ultimate pressure of below 5×10^{-7} torr. A Leybold E136 Roots pump is provided to give rapid initial evacuation to 10^{-4} torr. A complex system of safety interlocks, with multiple pressure sensors in all important regions of the vacuum system, causes automatic corrective actions to be taken in the event of certain failures occurring. In other, more serious circumstances, a rapid shut-down of the complete facility, including the thruster, is initiated.

As the system is intended for cyclic life-testing, with frequent, comprehensive measurements of all important properties of the exhaust plume, considerable care and ingenuity had to be taken in designing many different aspects of

the facility. For instance, novel arrangements were necessary for supporting the target and shrouds and for feeding liquid nitrogen to them, owing to the need to keep them electrically isolated over periods of many months in the presence of mercury. As a second example, a liquid mercury feed system had to be devised which can be rotated bodily through 90° as the top flange of the facility is rotated, without breaking the mercury columns leading to the vaporisers.

A power supply system is provided to both operate the thruster and appropriately bias the various electrically floating parts of the facility. As described in section 1.7.2, an electromagnetic sequencer is interposed between the thruster and the laboratory supplies to provide automatically a pre-set start-up sequence during cyclic testing. The sequencer also incorporates the control circuitry required during steady-state operation.

A CAMAC-controlled data acquisition system is provided, which can accept signals from either high or low potential sources (i.e. thruster or spacecraft reference in Fig.12); 64 channels are available in each case. As well as the unit-gain isolation amplifiers necessary to transfer the high voltage reference signals to low voltage reference, the system also contains variable filter components, programmable gain amplifiers, sample and hold modules to increase bandwidth, and automatic calibration equipment. The whole system, including the calibration, and the gain and bandwidth selection, is controlled by a Minimod computer. This computer also controls the overall progress of a cyclic life-test, including the operation of the electromechanical sequencer, and performs calculations of derived data for subsequent print-out or for plotting on an X-Y recorder.

The probe system is probably the most comprehensive ever fitted to a single ion thruster test facility. The positions of many of the probes are illustrated in Fig.54 and brief details of them are given below. A major requirement in designing the probes and their mounting arrangements was the need to cater for an uninterrupted life-test, and minimal perturbation of the thruster or its exhaust. Thus probes had to be kept out of the ion beam, except when in use, and any probe likely to require servicing or periodic inspection had to be provided with an independently-pumped vacuum lock. Thus the overall system is complex, and its design, construction and test required a great deal of effort.

The probes indicated in Fig.54 are as follows:

A Three azimuthal probe packages at angles ϕ of 90°, 180° and 270° to an arbitrary reference radius. Those at 90° and 270° are removable through

vacuum locks. These packages house sputter collection plaques at $\theta = 55^{o}$ (the direction of peak sputter measured for T4A) and ion probes at $\theta = 70^{o}$, θ being the angle between the thruster axis and a line joining the centre of the accel grid and the probe in question.

B An ion beam current probe which is parallel to the thruster axis. It moves from $z < 0$ to $z = 40cm$ and from $R = 0$ to $R = 30cm$, where R is the radial position and z the distance from the accel grid. It measures beam divergence, amongst other parameters. It is parked upstream of the thruster when not in use.

C This is a collimator stack, which is mounted at $\phi = 0$, $R = 40cm$. It is basically a housing for collimators which can observe the accel grid of the thruster with angles θ ranging from 35^{o} to 85^{o}, and has recently been modified to reach $\theta = 105^{o}$. It may be heated to about $5^{o}C$ or cooled with liquid nitrogen, and is provided with a vacuum lock for the removal of samples. The collimators can be used for the measurement of the materials sputtered from the thruster or of the neutral mercury efflux. In the latter case, oscillating quartz crystal detectors are housed in the stack; they require cryogenic cooling.

T A time-of-flight mass spectrometer for the measurement of the doubly-charged ion content of the beam. It is mounted on a 43cm radius arm and pivots about a shaft at $\phi = 90^{o}$. It can therefore scan across the beam. Its drive mechanism allows it to be raised above the thruster when not in use.

W This is a wide angle probe which measures high energy ion current or high plus low energy ion currents. It is mounted on a shaft at $\phi = 180^{o}$, and is shown in the upper view in Fig.54 at $\theta = 0^{o}$ and in the lower at $\theta = 90^{o}$. The probe is at a distance $r \sim 40cm$ from the centre of the accel grid and swings over a range of angles from $\theta = -100^{o}$ to $\theta = +100^{o}$. Also shown in the lower view in Fig.54 is a version carrying additional ion current probes which view azimuthally when $\theta = \pm 90^{o}$.

It should be emphasised that the data obtainable from this system of probes is probably unsurpassed as regards overall coverage of the many particle species of interest and as regards accuracy. In addition, the fact that the thruster, target and cryoshrouds are all electrically floating ensures that the test conditions approximate very closely to those expected in orbit.

2.4.6 Component test facilities

Numerous small vacuum systems for testing cathodes, vaporisers and other components are available at the RAE, Culham and Mullard Ltd. Most of these facilities consist of a single oil or mercury diffusion pump of 10cm to 25cm nominal diameter, with a conventional backing pump, evacuating a glass or small stainless steel vessel. Between this vessel and the pump is usually situated a liquid nitrogen cooled trap for collecting any mercury flowing into the system. Some safety interlocks are usually provided; these tend to become more comprehensive if life-testing is carried out. The ultimate vacuum achieved by such facilities is usually just below 10^{-6} torr, although the RAE possesses two with a 10^{-8} torr capability.

The most advanced facility available was designed for cathode testing by Mullard Ltd. It consists basically of a large stainless steel chamber with a central liquid nitrogen cooled mercury vapour trap. Leading off this chamber are eight individual smaller chambers, each having its own high vacuum valve and auxiliary pumping line. The cathode mounted in each of the smaller chambers can thus be operated or examined in isolation, if necessary.

2.4.7 Environmental test facilities

As most of the aerospace organisations in the UK have available the usual vibration and acceleration test equipment, together with numerous small, general purpose vacuum chambers, no attempt will be made to detail these here. For the same reason, no reference will be made to the locations or capabilities of the electrical and electromagnetic test facilities available. This section will be restricted to giving brief details of two large vacuum facilities at the RAE, which are not duplicated elsewhere in the UK.

The first of these facilities to be constructed was the 2.5m diameter space simulation chamber shown in Fig.55. This is designed to house a complete spacecraft and to subject it to extreme cold and to simulated solar radiation. The horizontal vacuum chamber is nearly 10m long and is pumped by two 0.9m diameter oil diffusion pumps, via watercooled baffles and liquid nitrogen cooled traps. There are no high vacuum valves. The chamber, including the door, is lined internally with black-painted aluminium shrouds, which are supplied automatically with liquid nitrogen from an external tank. The ultimate vacuum of the chamber if about 10^{-6} torr.

To provide solar simulation, six 30kW carbon arc lamps are fitted to ports at one end of the chamber. These can illuminate an area 2.5m in diameter with the equivalent intensity of 1.5 suns.

The spacecraft or other device to be tested is mounted on the end of a horizontal 'sting', which can carry up to 1000kg. The spacecraft can be rotated through $\pm 1\frac{1}{2}$ revolutions about its longitudinal axis, and this axis can be rotated by $\pm 180^{\circ}$ so as to alter the angle of incidence of the radiation from the arc lamps.

A console provides remote control of the pumping and cryogenic systems, together with control of the motion of the spacecraft and monitoring of the solar simulation. Numerous safety interlocks are provided. A 100 channel data logger monitors the temperatures and other parameters generated by a test. Chart recorders and automatic temperature controllers are also incorporated to provide extensive monitoring and controlling facilities.

The other space simulation facility to be mentioned, which is housed in the same building, is a 3m diameter thermal soak chamber. This can be evacuated to 10^{-6} torr and is completely lined with black-painted stainless steel shrouds which can be maintained at any temperature between -50°C and $+90^{\circ}$C. The maximum rate of temperature change is 20°C per hour.

Joined to the thermal soak chamber via an accurately controllable valve is a rapid decompression test chamber. This can accommodate equipment up to 1.2m diameter and 1.5m long, and is used to simulate the pressure change experienced by a spacecraft during launch.

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3 DEVELOPMENT PROGRAMME

3.1 Assumptions upon which programme is based

The ion thruster system development programme in this Report has been planned to meet the following requirements:-

(i) An ion thruster system, consisting of two thrusters and one pcu incorporating some passive and standby redundancy, shall be prepared and suitably tested for an experimental flight on a satellite, which is to be launched in December 1980. To meet this date the ion thruster system shall be delivered to the satellite builder some 12 months earlier.

(ii) The ion thruster system for the experimental flight shall have the capacity to provide nssk for the same period as would be achieved when using the same mass of hydrazine as the mass of the ion thruster system.

(iii) Complete flight and flight spare ion thruster systems, each consisting of four thrusters and two pcus with a high level of redundancy, shall be prepared and suitably tested for operational use in a satellite which is to be launched in mid 1983. To meet this date the flight ion thruster system shall be delivered to the satellite builder some 18 months earlier, and the flight spare system about 9 months before launch.

(iv) The operational system shall be capable of fulfilling the mission requirements specified by ESTEC in Mission Model TCA/CAM/76.275/mb of 5 April 1976.

(v) All components and equipment to be used on both the experimental and the operational flights shall be previously qualified formally. In addition, before both flights, at least two thrusters and pcus shall have been life tested for at least twice the number of hours' operation and starts as will be required for the respective missions.

(vi) The qualification procedure and thruster-pcu life testing shall be supported by adequate life testing of critical thruster components, where necessary. Where possible, high-reliability electronic components complying with the standards laid down by the ESTEC Space Components Co-ordinating Group will be used.

(vii) The entire development, manufacturing and testing of the ion thruster system, up to the time when deliveries are made to the satellite builder, shall be conducted within the UK. However, this does not exclude

the procurement of special materials, or electronic components, from outside the UK. This assumption can be changed if it is desired to spread the work into other countries, but obviously this would alter the programme and its costs.

(viii) The current process of transferring to industry the responsibilities for the programme and the expertise presently available at Culham and RAE, shall be continued as far as is feasible; but both Culham and RAE will continue to provide active support in this field until at least the first operational flight is achieved.

3.2 Description of programme

The proposed development programme to meet ESTEC's requirements and the assumptions detailed in section 3.1 is shown in Fig.56, which is backdated to 1 March 1976, so as to indicate some of the work already in hand. These plans are a logical continuation of the existing ion thruster work currently in progress, for which there are already many thrusters and other system components in various stages of manufacture and testing. The programme is therefore designed to make the best use of existing expertise and equipment.

As requested by ESTEC, Fig.56 shows the various technical aspects and phases of the programme broken down into work packages which are readily identifiable as being necessary to achieve successful test and operational flights.

Unfortunately, Fig.56 has to be somewhat complicated in order to show the many interactions between the various parts of the programme. Particularly is this necessary in order to determine the amount of hardware which is required and to establish that reasonably continuous, but not duplicated, use is made of the various UK test facilities, teams, and manufacturing resources. Even so, many of the interactions between the various aspects of the programme have been omitted from Fig.56 for the sake of clarity.

Study of this programme will reveal that most of the work falls into four main areas; this is because technical considerations tend to produce this type of grouping and, as a result, over the years, the UK teams and resources have been built up to match this distribution.

The four main areas identifiable in Fig.56 are:-

(i) Thruster components.

(ii) Development and manufacture of thrusters, combined with testing of the thrusters and the complete system.

(iii) Development, manufacture and testing of the electronic systems. Because of the dual role concerning thrusters and electronics played by the RAE with its 1.5m test facility, some of the thruster R&D also appears in this area.

(iv) Development, manufacture and testing of propellant system components.

The work of integrating the ion thruster system into the satellite is also shown in Fig.56, for the sake of completeness. However, some of this activity might be considered as part of the satellite project, rather than the ion thruster development programme.

3.2.1 Thruster components

Fig.56 shows that most of the new work on thruster components is concerned with life testing and the manufacture of components for the 23 thrusters used in the programme. This is because so much development and testing has already been done on these components that it is considered that they have reached a status where only further extensive life and qualification testing will reveal the need for any further development.

Most of the thruster component work is currently undertaken by the Mullard Central Materials Laboratory. However, MSDS, who are expected to act as prime contractor on this project, wish to have a second supplier for these critical components. It is therefore intended, as shown, to build up a similar competence in the Hirst Laboratories of the GEC.

3.2.2 Thruster and complete systems

These two aspects naturally fall into the same group as they need identical test facilities. One of the salient features of this area (Fig.56) is the anticipated 24-month commitment by the Culham Laboratory, to the Comsat Corporation, of their 1.2m chamber for a very extensive life and diagnostic test of a T4A thruster. Either in parallel with this life test, or before if time permits, Culham will also complete the optimisation of the location of the neutraliser on the thruster and of its operating conditions. Later in the programme, as will be seen, Culham's role is to explore fully the beam characteristics of the T5 and projected T6 thrusters, as well as conduct extensive life tests on both of them.

RAE are currently building three of the new T5 thrusters for development purposes. These will be used for electronic integration work, and for mechanical,

performance and life tests at RAE, MSDS and FRI. The information derived from these activities will be used by MSDS to update the design of T5 and to build two further thrusters; one of these will be life tested for 1500 hours with 500 starts at FRI, and the other will be subjected to environmental and performance tests by MSDS.

It will be noticed in Fig.56 that it is proposed to install a 1m diameter chamber at MSDS in 1977 and to fit it with a mercury pool target. This will enable MSDS to conduct an increasing share of the performance, life and acceptance testing, as part of the planned technology transfer to Industry.

Following the work on the first T5 thrusters built by MSDS, they are to build 5 more; two of these will be subjected to life tests of 1500 hours and 500 starts, one is to be formally qualified, and the remaining two will be acceptance tested and delivered for an experimental flight.

It is felt that the two thrusters which are to be used for the experimental flight need not have redundant propellant feeds, i.e. duplicated cathodes, neutralisers and main flow assemblies. However, it is considered highly desirable that the operational thrusters should have duplicated feed systems, as far as development work shows this to be feasible. This qualifying remark is included, as it is not yet known whether twin cathodes can be fitted without significantly impairing the performance of the thruster; there does not appear to be any difficulty about installing redundant neutralisers and main flow assemblies, so this is obviously desirable.

Design schemes incorporating redundant thruster components already exist, and it is proposed that, about the end of 1977, the RAE should start experimental work on these, with the aim of including them in the operational thruster, tentatively designated T6. This work should be extended to include performance and life testing at Culham, FRI and MSDS, as well as the normal qualification procedures, in time for an operational launch in mid 1983.

3.2.3 Electronic systems

MSDS have already built a breadboard pcu system, which has been tested successfully on the T4A thruster. However, as a result of these tests and further work on starting techniques, it is now known that the system needs updating to meet the latest requirements. Accordingly, joint MSDS/RAE work has started to update and integrate the breadboard pcu with one of the new T5 thrusters.

In parallel with this, MSDS will start the design and building of a packaged pcu, including some provision for passive and standby redundancy. This unit will then be tested with the first MSDS-built T5 at FRI. Subsequently, MSDS will build four more packaged pcus for use in life tests, for qualification, and for the experimental flight.

At a later date, work is to start on an updated pcu to match the requirements of the T6 thruster with twin propellant feed systems. It is hoped that some flight data can be obtained in time to incorporate such improvements as seem necessary in the pcus which are to be used in the operational flight. The relevant details of this part of the programme are also included in Fig.56.

In parallel, and continuing almost throughout the programme, further work is planned on the thruster simulator. It is envisaged that this will form a key part of the check-out equipment, which is to be built by MSDS and used for integrating and testing the ion thruster system in a satellite.

3.2.4 Propellant system

Two engineering model, 5kg capacity mercury tanks are being built to RAE drawings by Sealol Ltd. It is intended that RAE will conduct performance and vibration tests on these tanks in 1976/7 and the resulting data will then be given to Industry to enable two batches of flight quality tanks to be produced. Units from the first batch will be used for proving the design, and for qualification and the experimental flight. The second batch will also be proved and then used in the operational mission.

It is anticipated that several latching mercury stop valves will be required for the flight propellant feed systems. Initial development work is starting on these in the RAE and it is planned to pass the resulting data to HSD in 1977 for them to complete the development, production and qualification of these valves.

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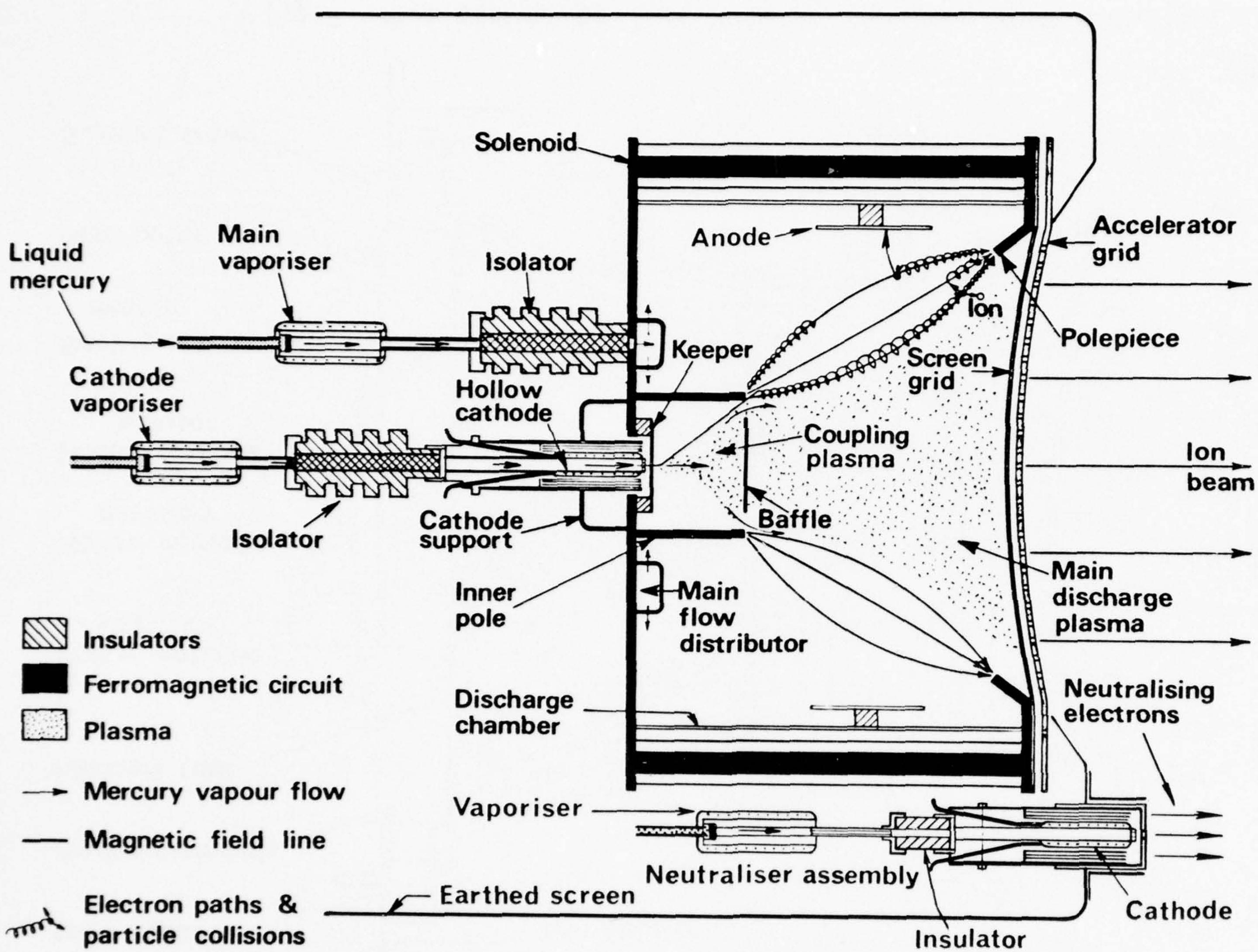

Fig. 1 Schematic of T4A 10 cm Ion thruster showing main components

Fig. 2

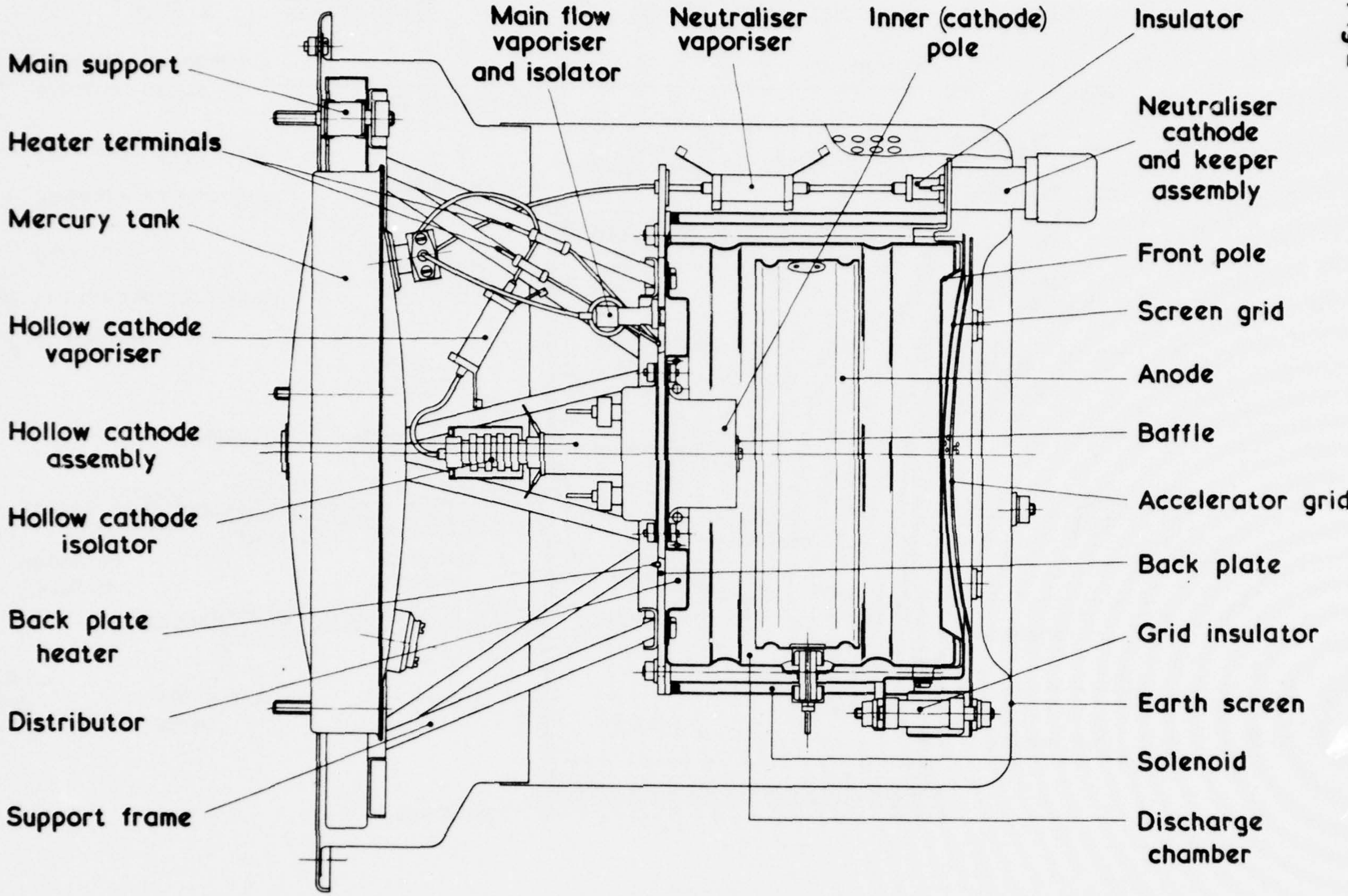

Fig. 2 Part section of T4A thruster, complete with propellant tank

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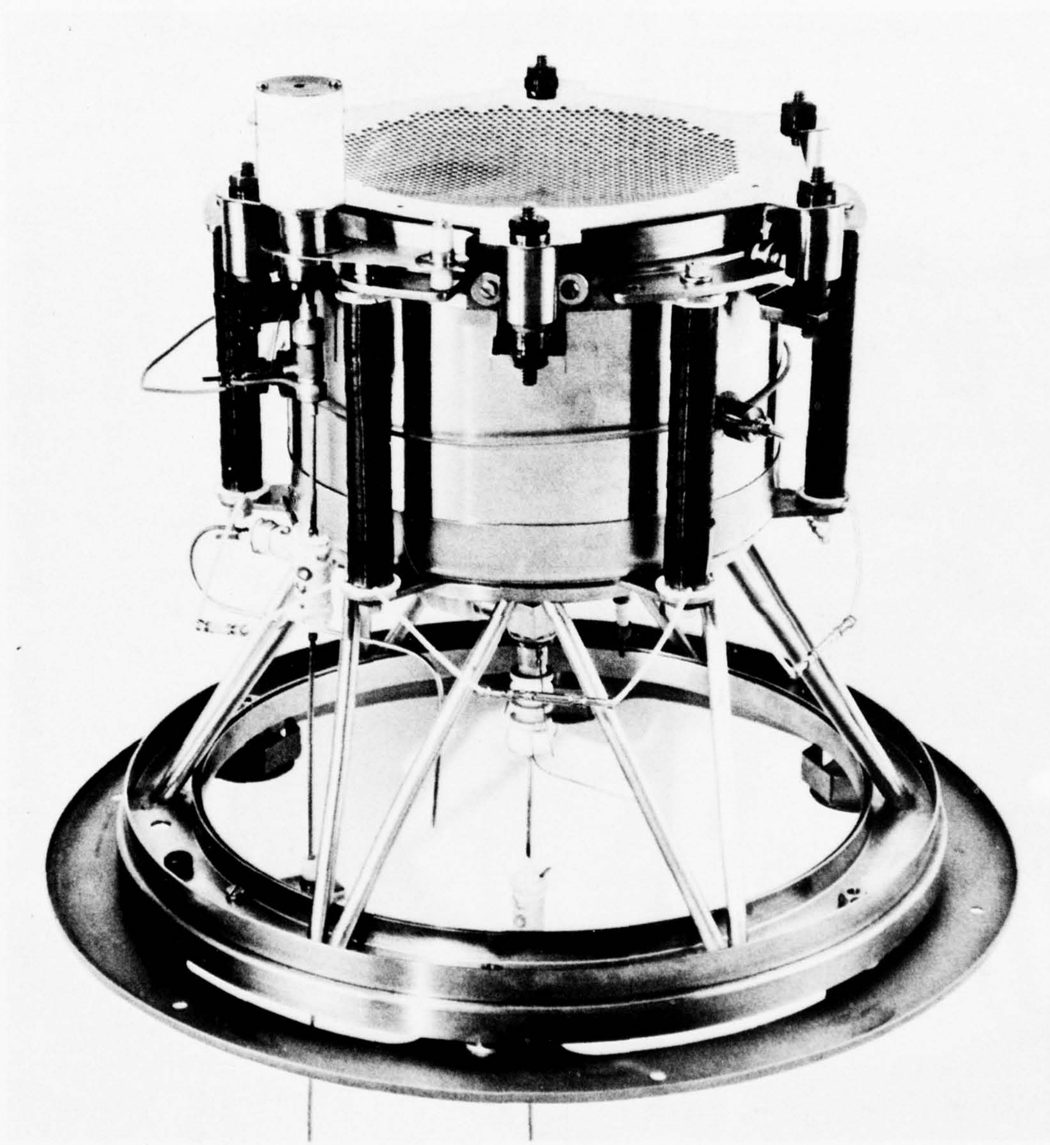

Fig 3 T4A thruster without earth screen and propellant tank. The neutraliser is an early laboratory test version, and isolator heat shields and heaters are not fitted

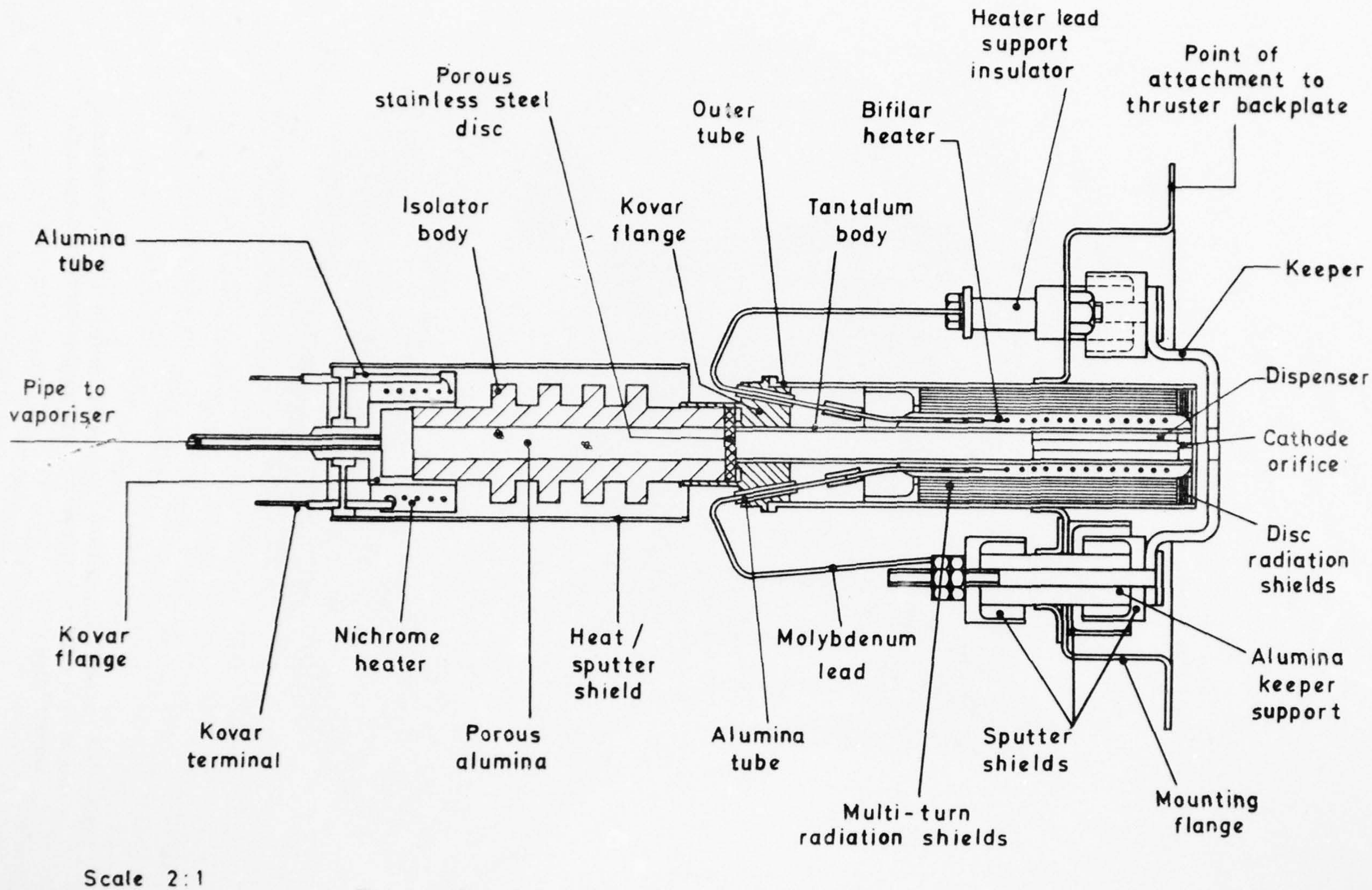

Fig.4 Section through cathode / isolator assembly

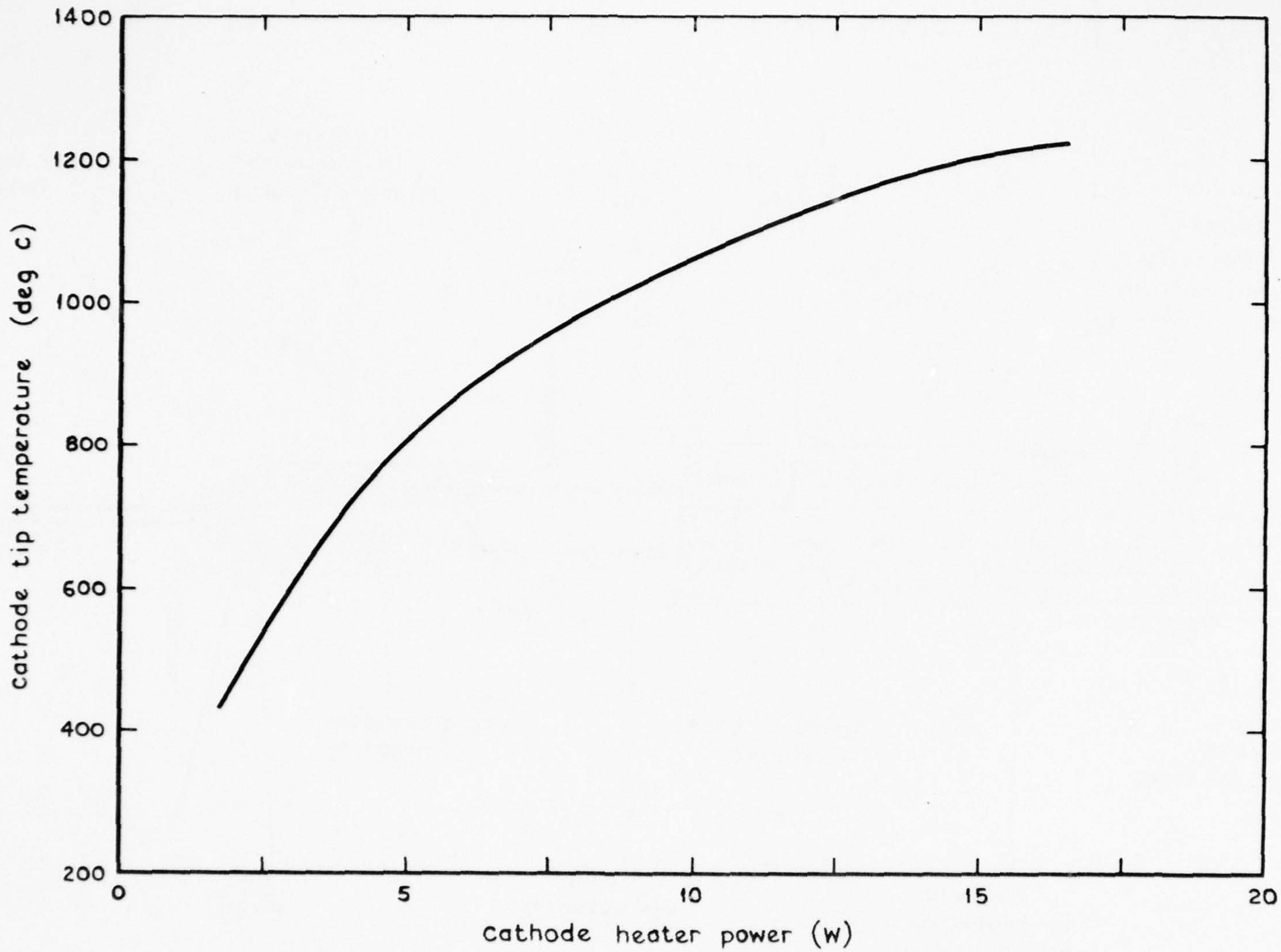

Fig. 5 Cathode tip temperature as a function of heat power

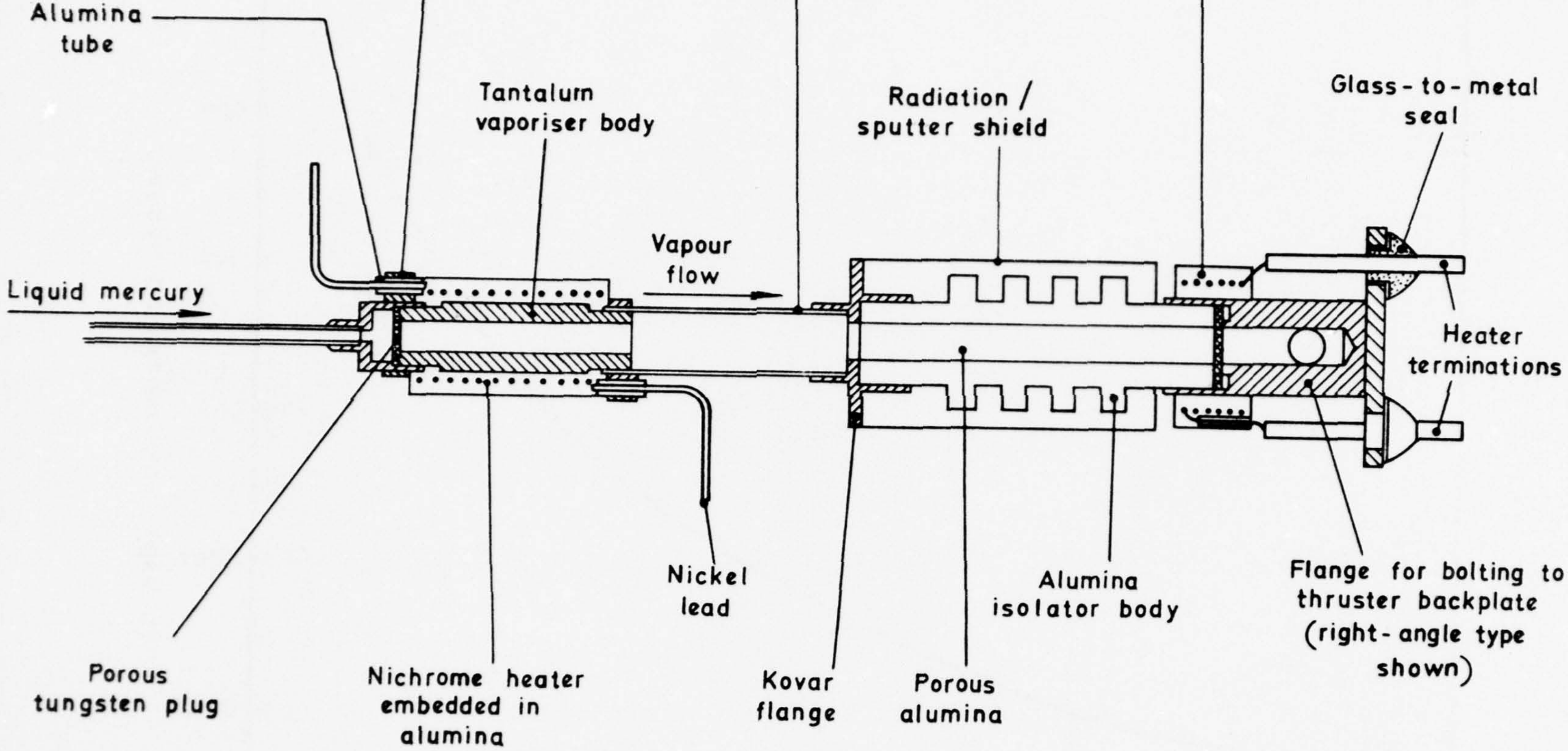

Fig.6 Section through main flow vaporiser/isolator assembly

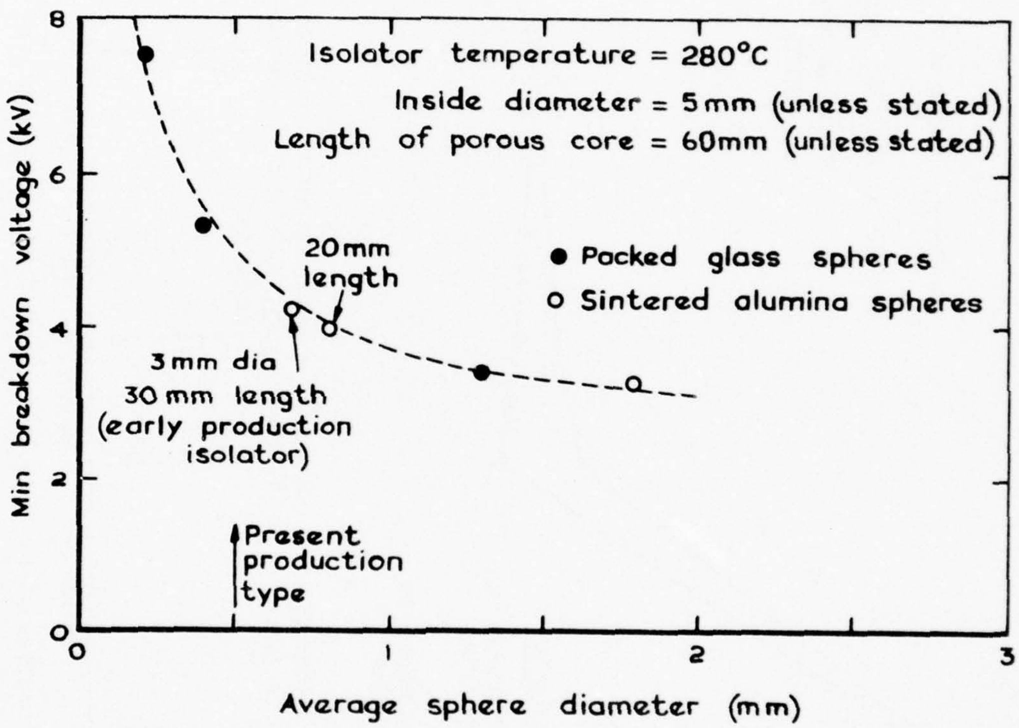

Fig. 7 Minimum breakdown voltage as a function of sphere size for porous structure electrical isolators

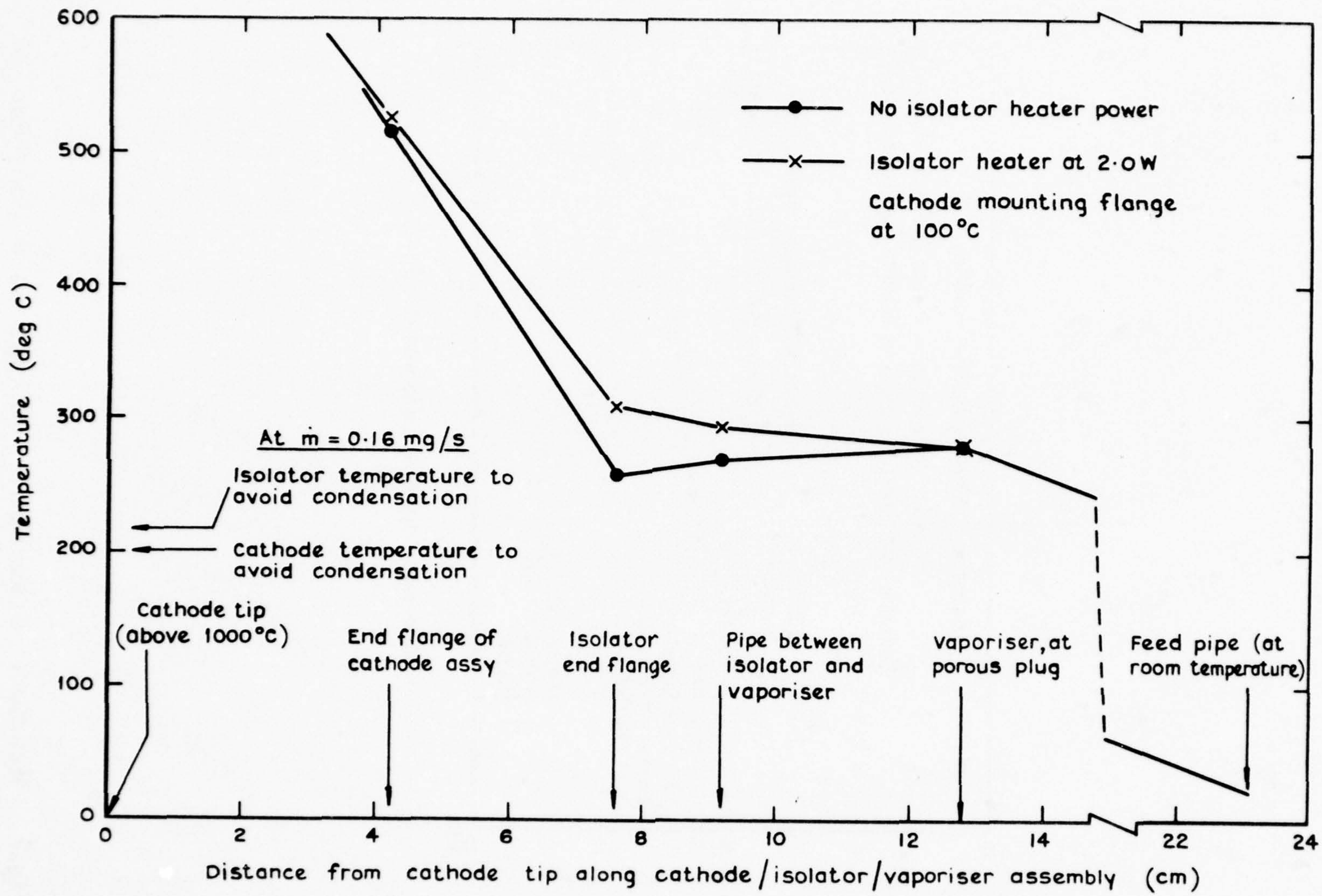

Fig.8 Temperature distributions along cathode/isolator/vaporiser assembly

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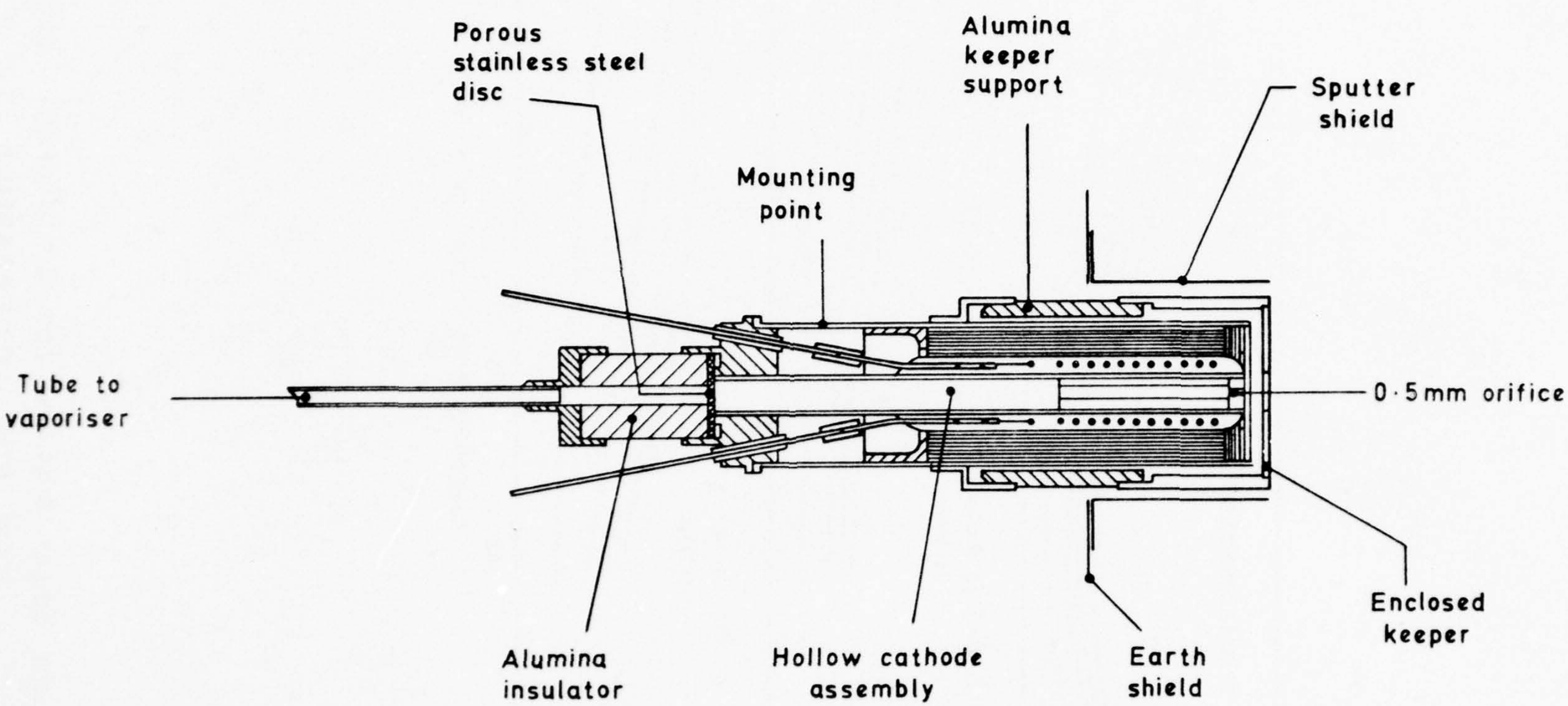

Scale 2:1

Fig. 9 Section through neutraliser assembly

Fig. 10

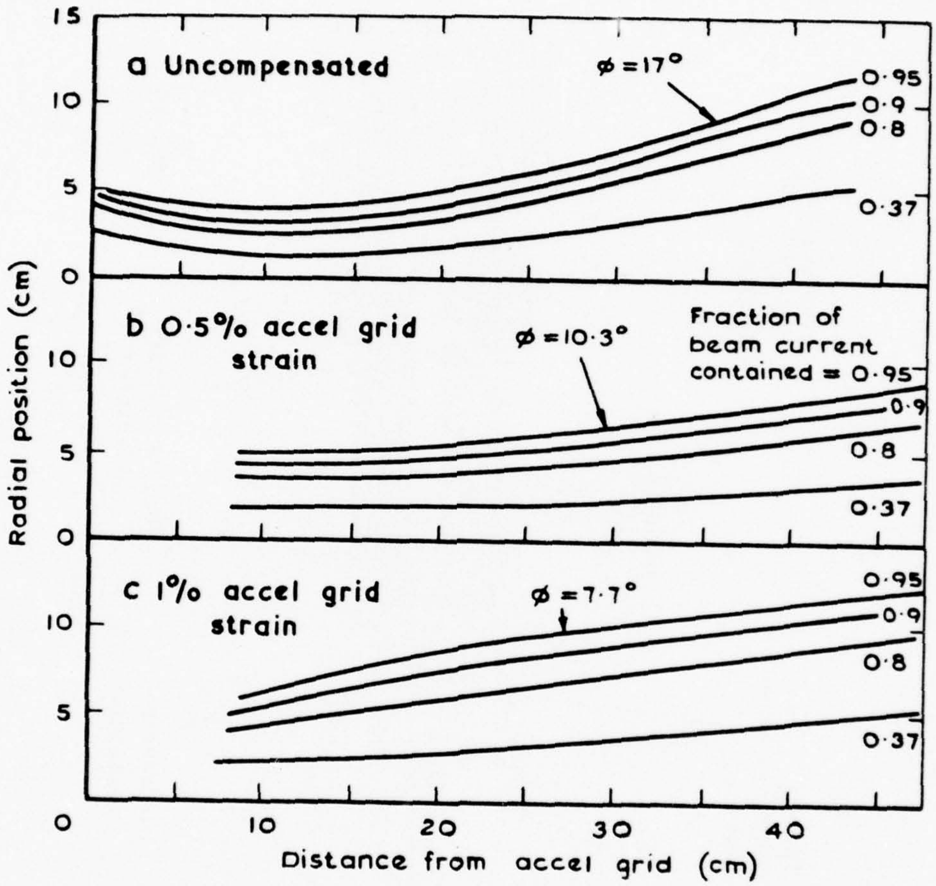

Fig.10 Ion beam profiles for 3 different degrees of accel grid compensation

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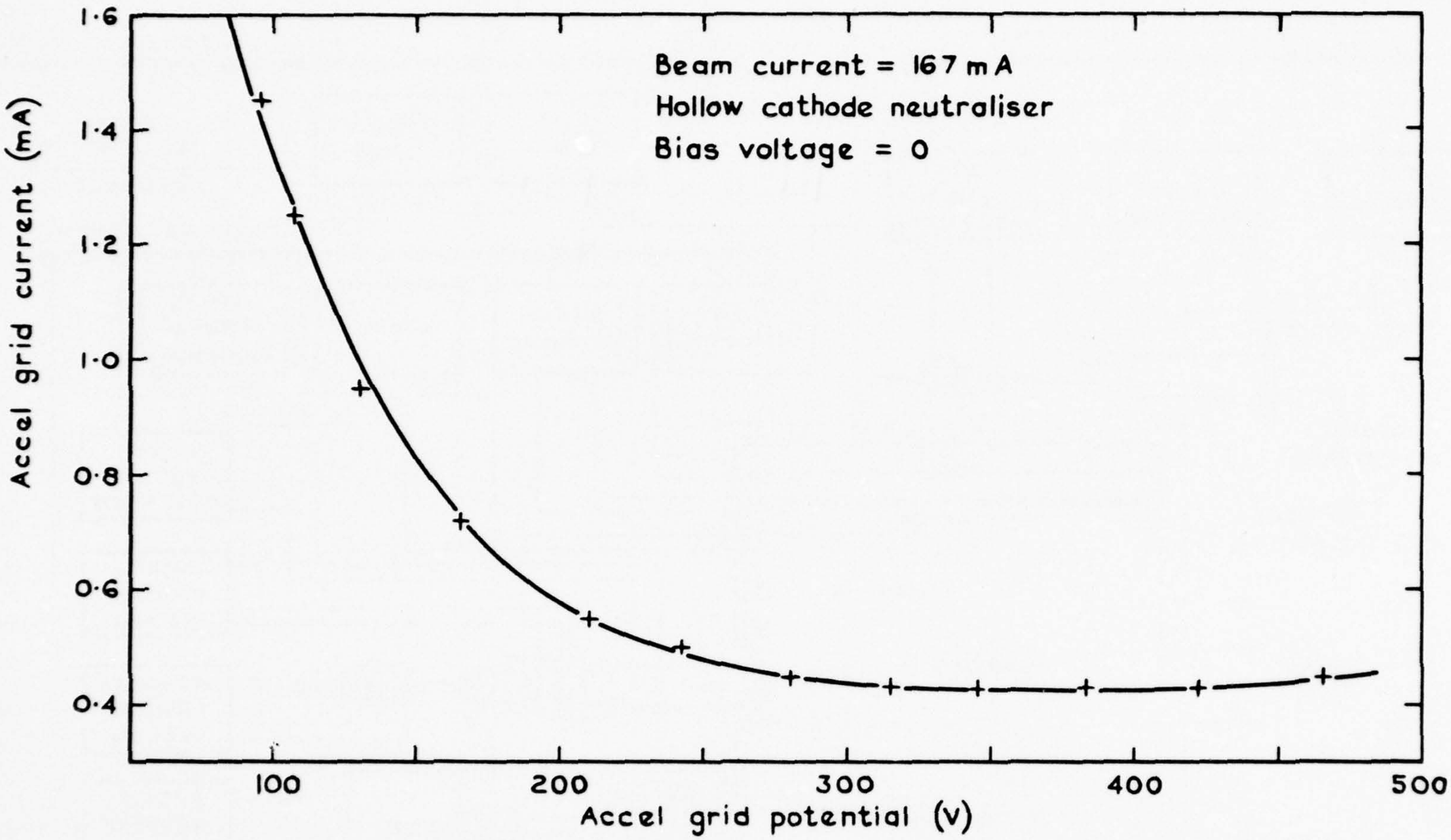


Fig.11 Accel grid voltage - current characteristic for 0·5% compensation

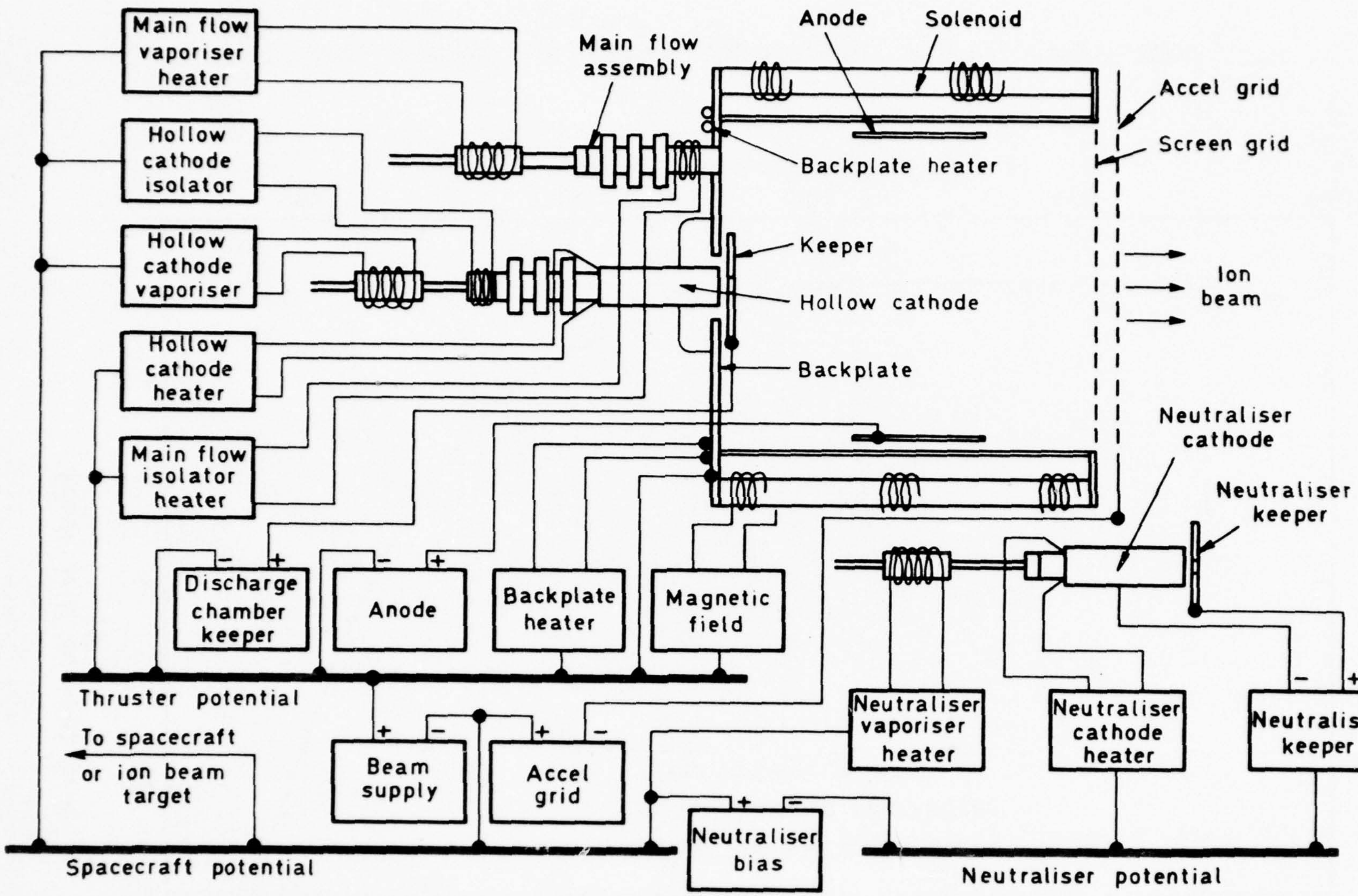
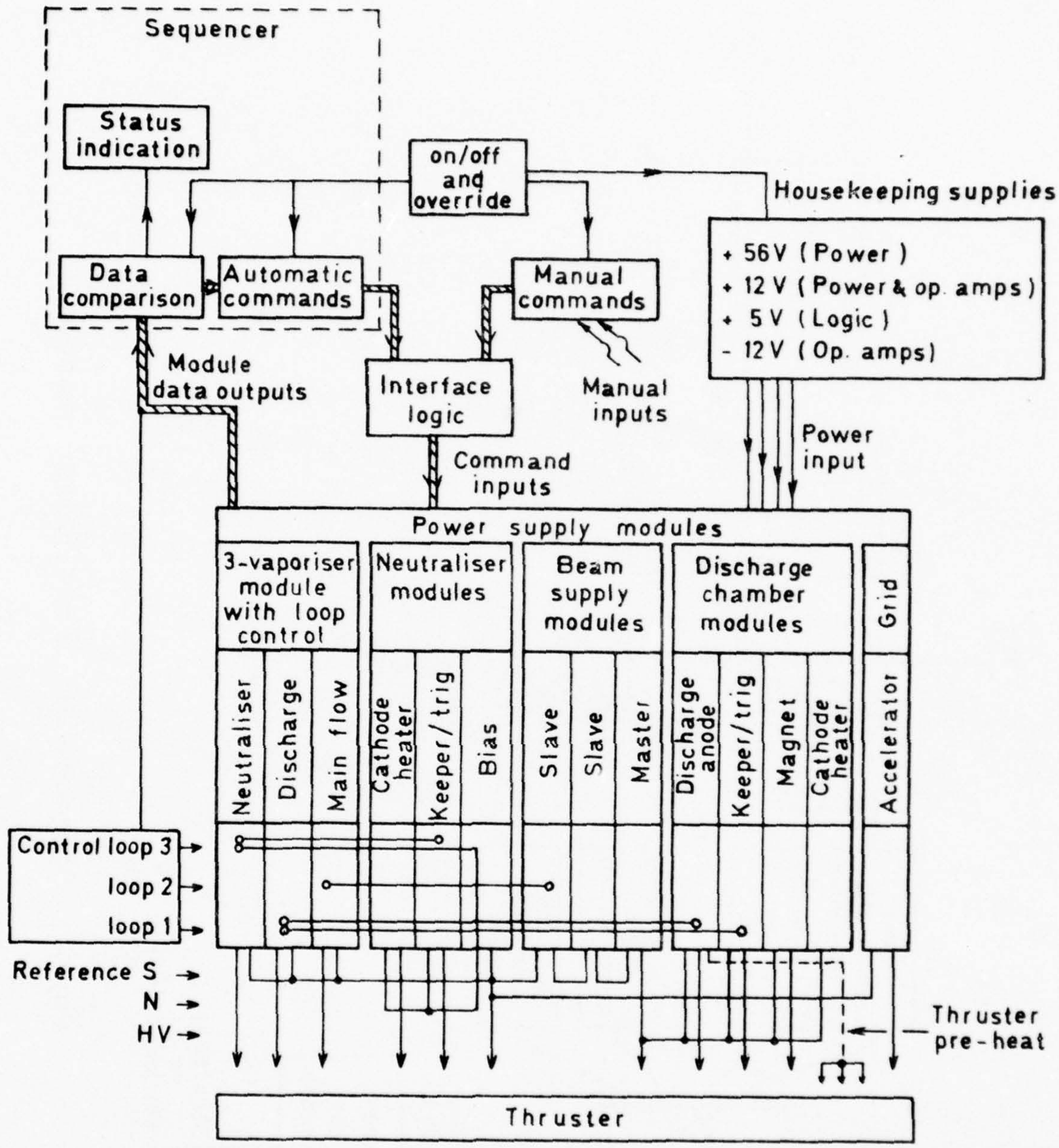


Fig.12 Schematic of thruster, showing connections of power supplies



Reference potentials

S - Spacecraft potential (may be earthed in non-floating experiments)

N - Nuetraliser bias potential

HV - Beam supply potential (thruster body)

Fig. 13 Schematic of power conditioning unit

Fig. 14

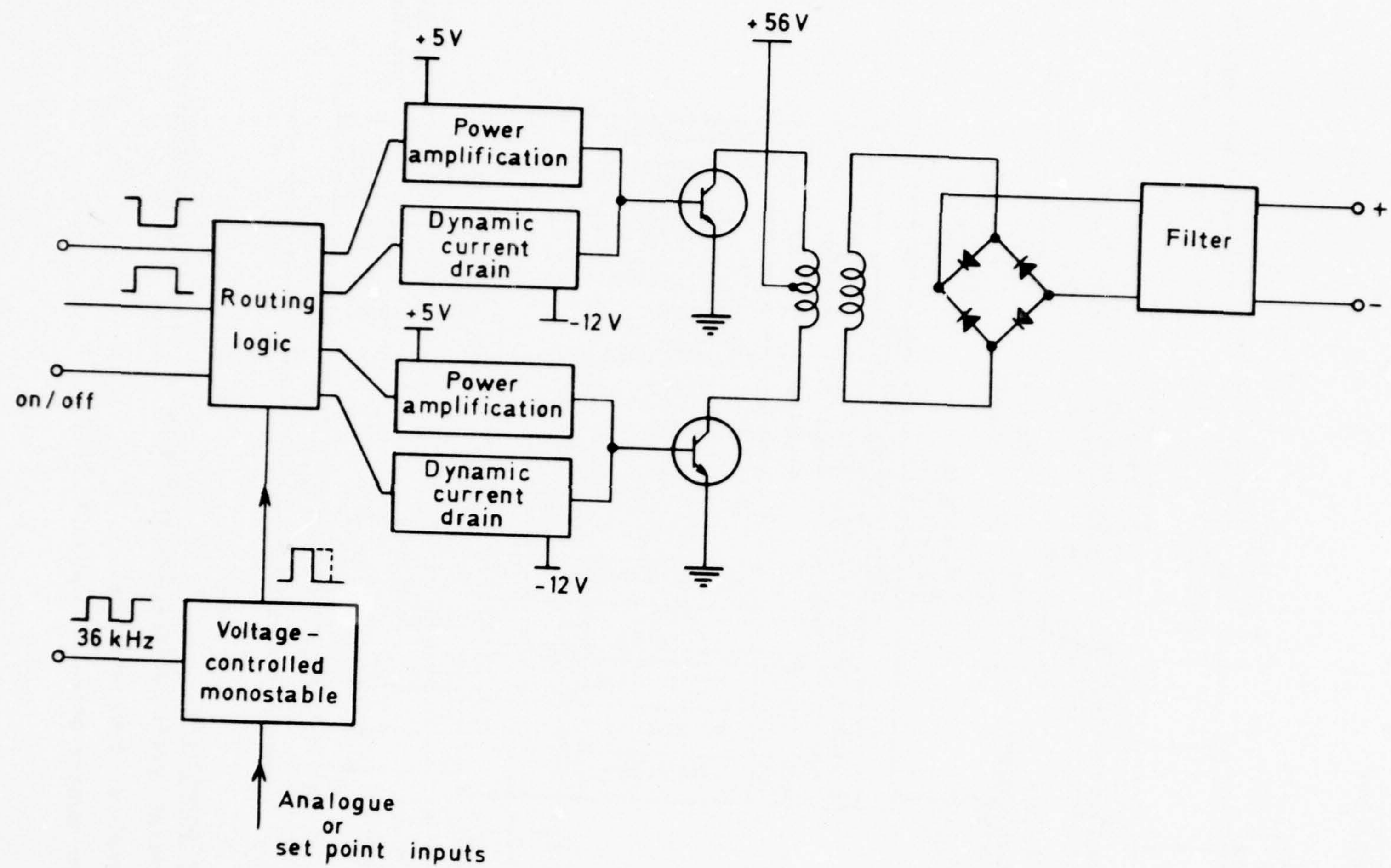


Fig. 14 Schematic of PWM power module

TR 77063

Fig. 15

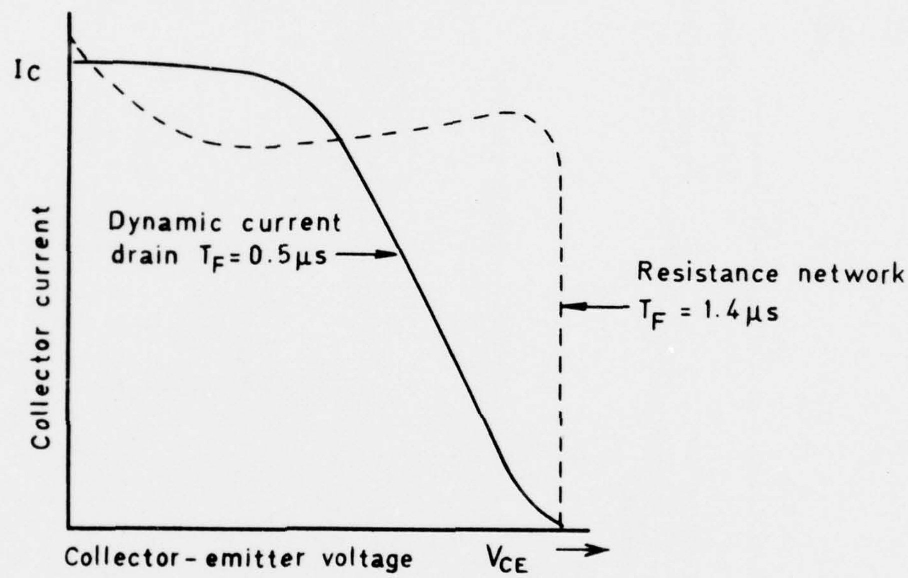


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Fig. 15 Curves showing advantage of using dynamic current drain for power transistors

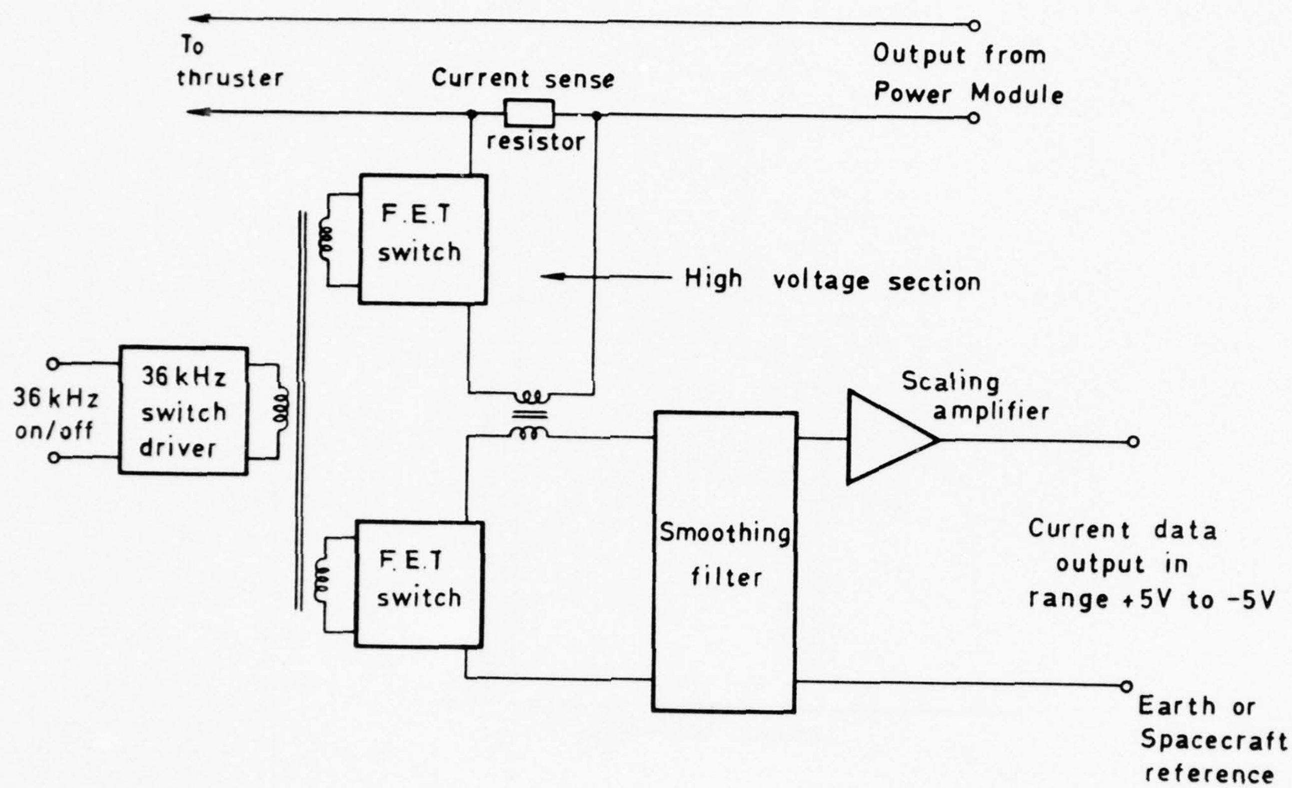

Fig. 16 Current isolator circuit

Fig.17

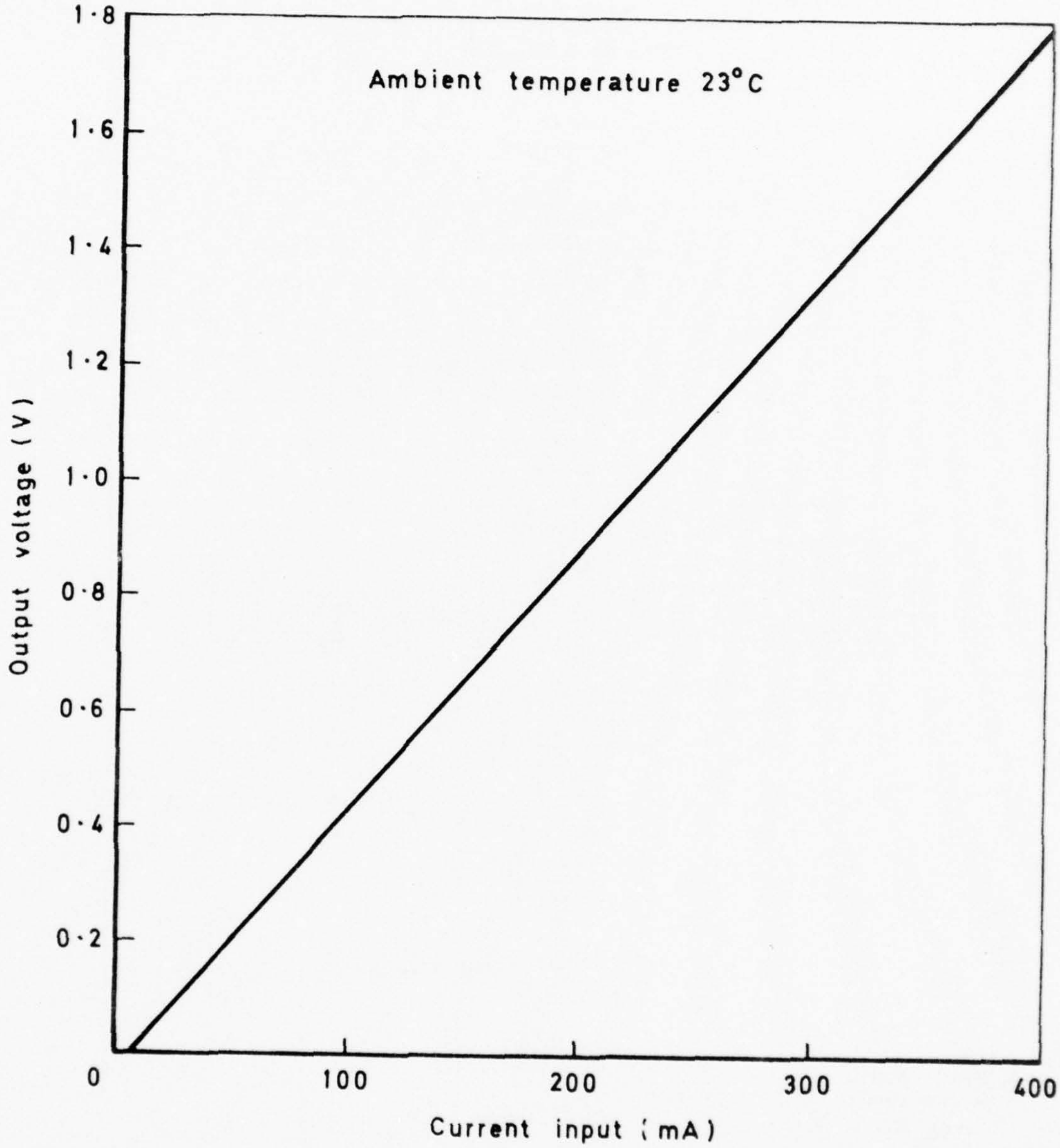

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Fig. 17 Calibration curve of solenoid supply current isolator

004 906084

Fig. 18

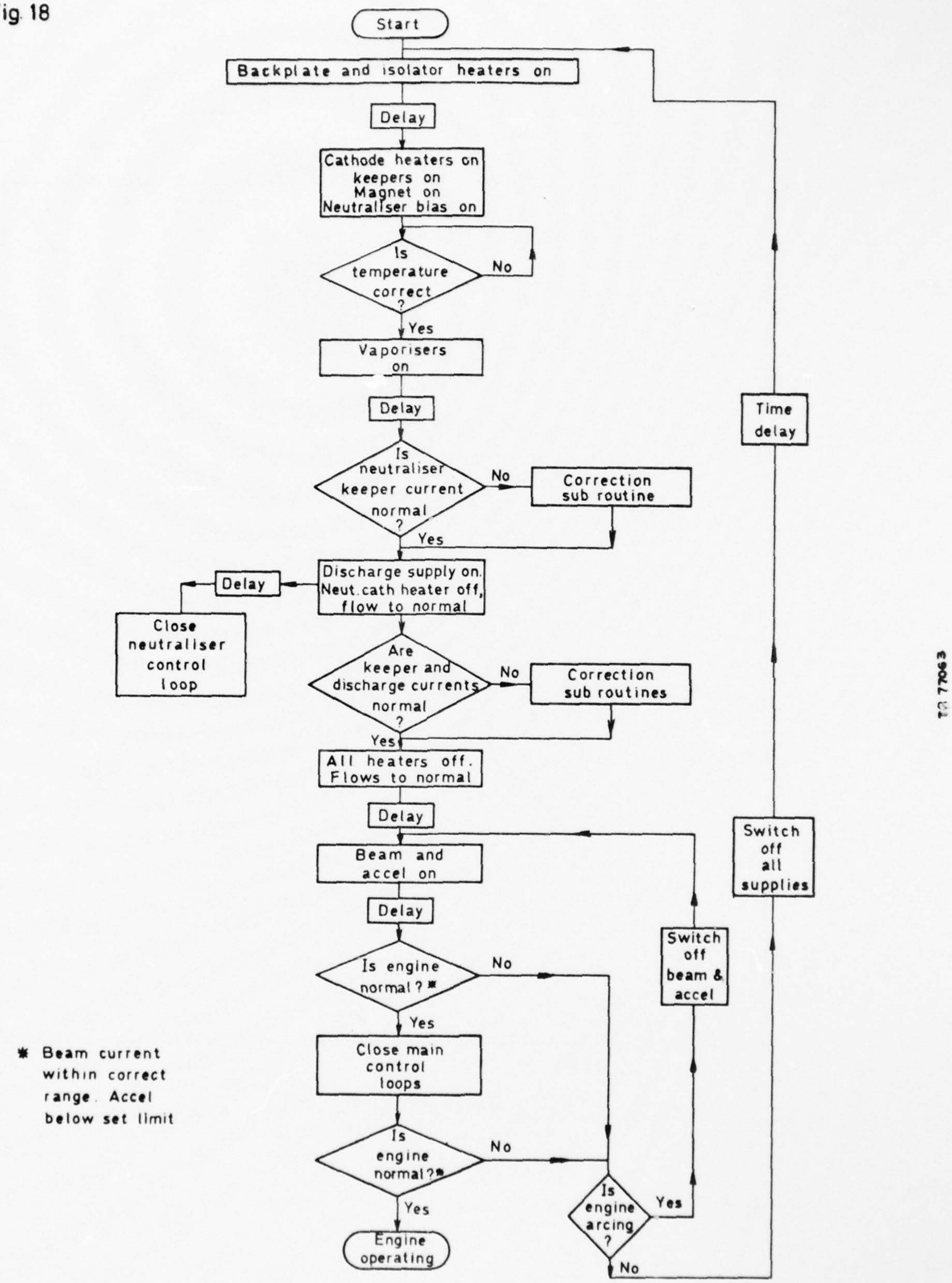
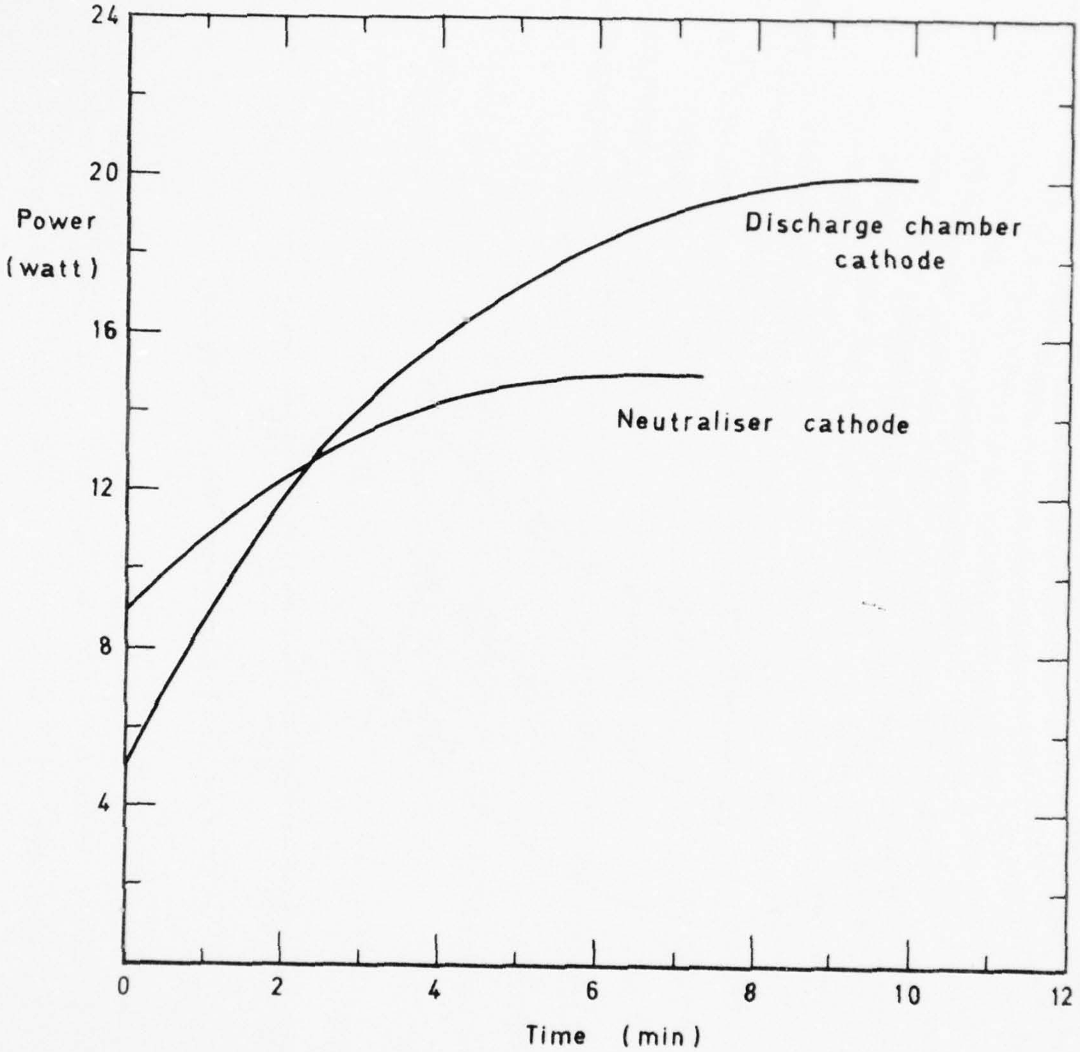


Fig. 18 Simplified hard-wired start-up sequence



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004 906068

Fig. 19 Cathode heater power as a function of time for neutraliser and discharge chamber cathodes

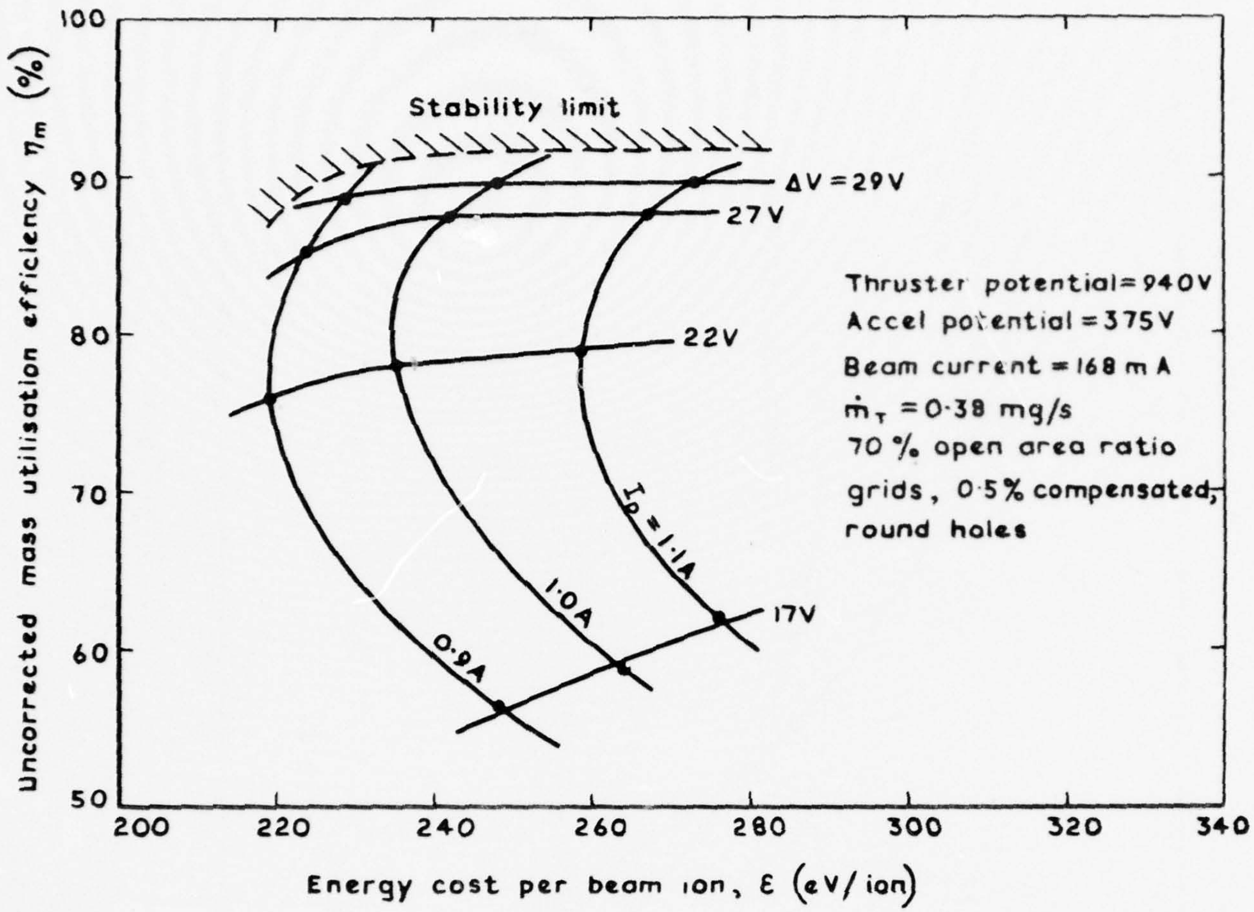

Fig.20 Mass utilisation efficiency as a function of energy cost per beam ion at the end of the second 1000 hour life-test

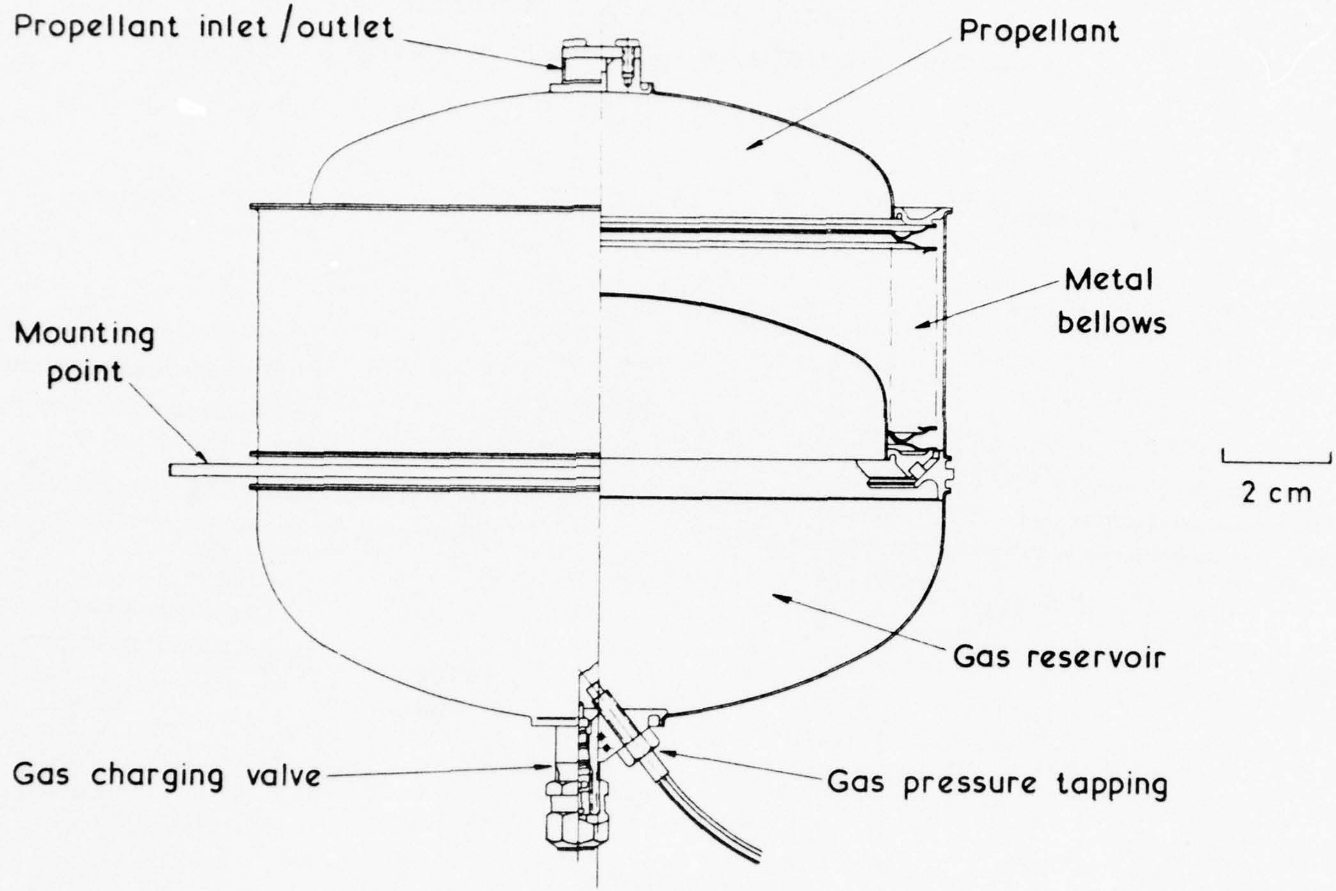

Fig. 21 Mercury propellant tank

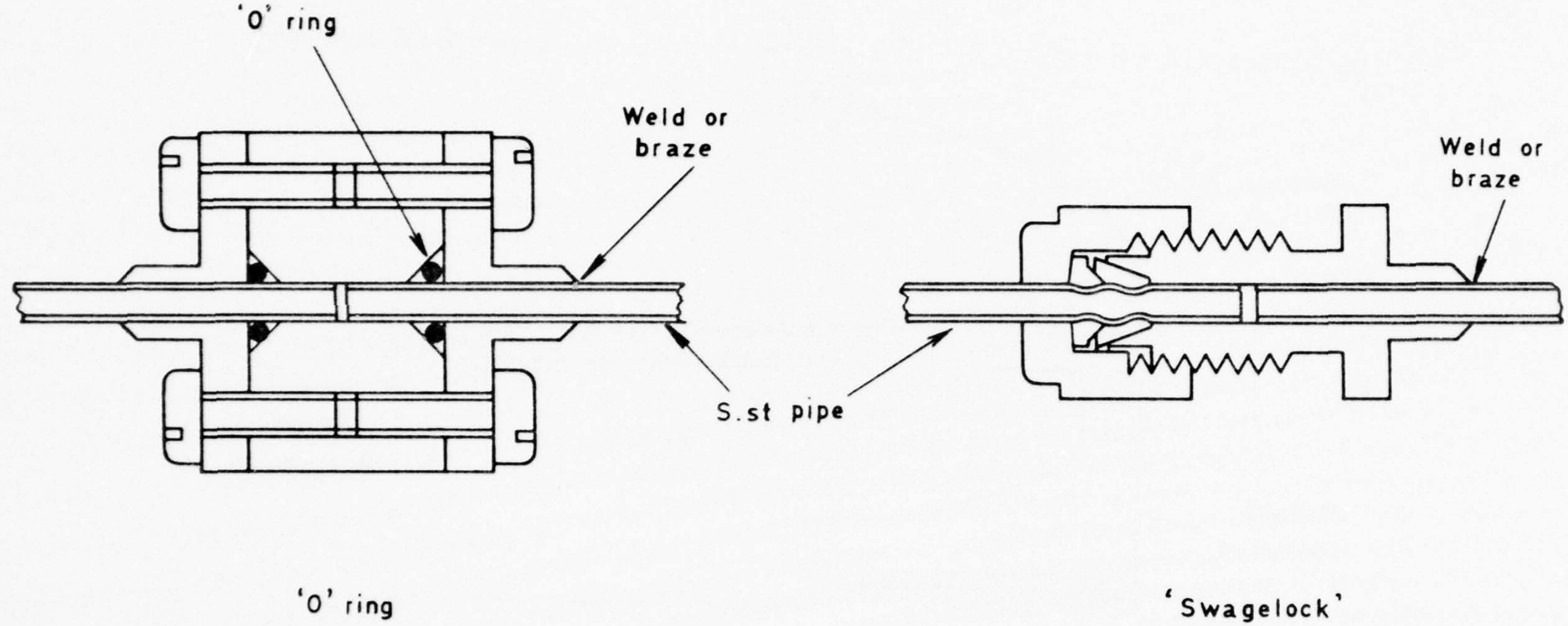

Fig.22 Typical 'O' ring and 'swagelock' couplings for mercury propellant pipelines

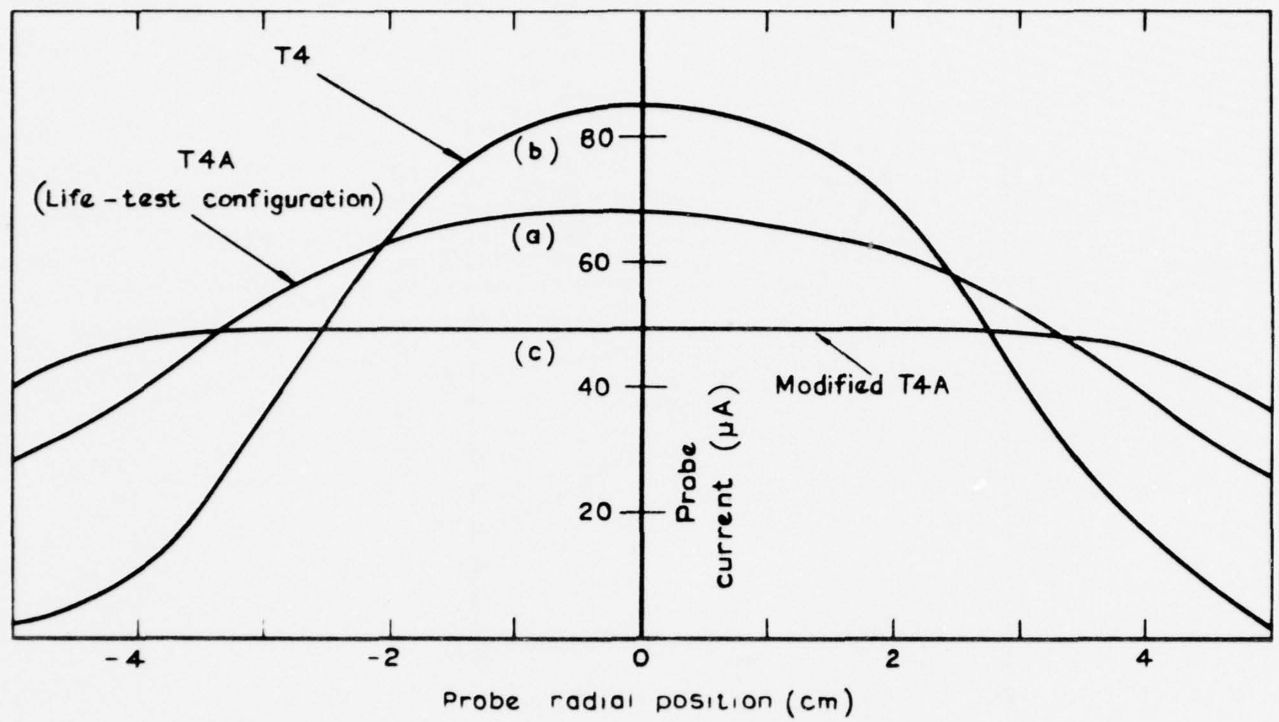

Fig 23 Radial density profiles within the discharge chamber close to the screen grid, as indicated by a Langmuir probe

Fig. 24

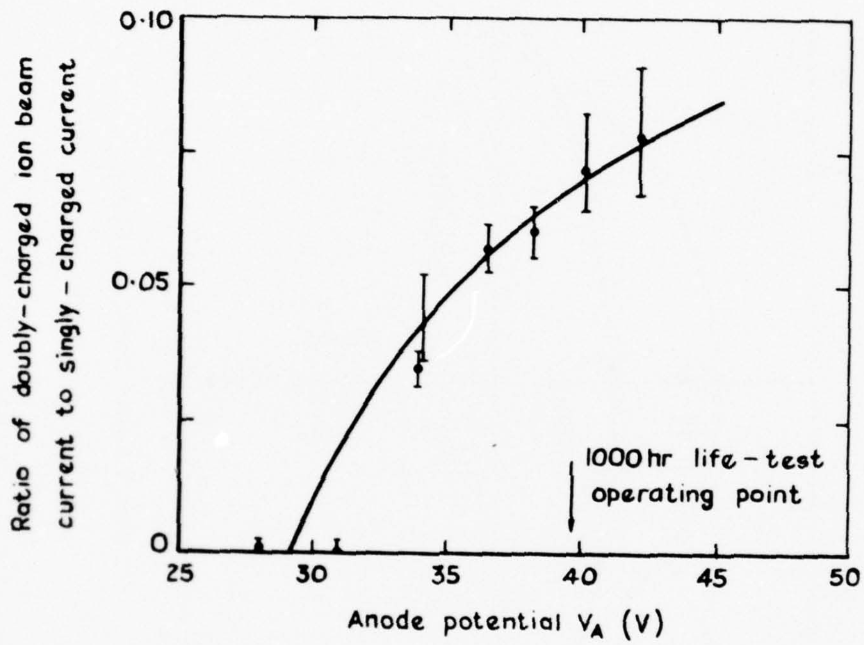

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Fig. 24 Ratio of doubly-charged ion beam current to singly charged current as a function of anode voltage

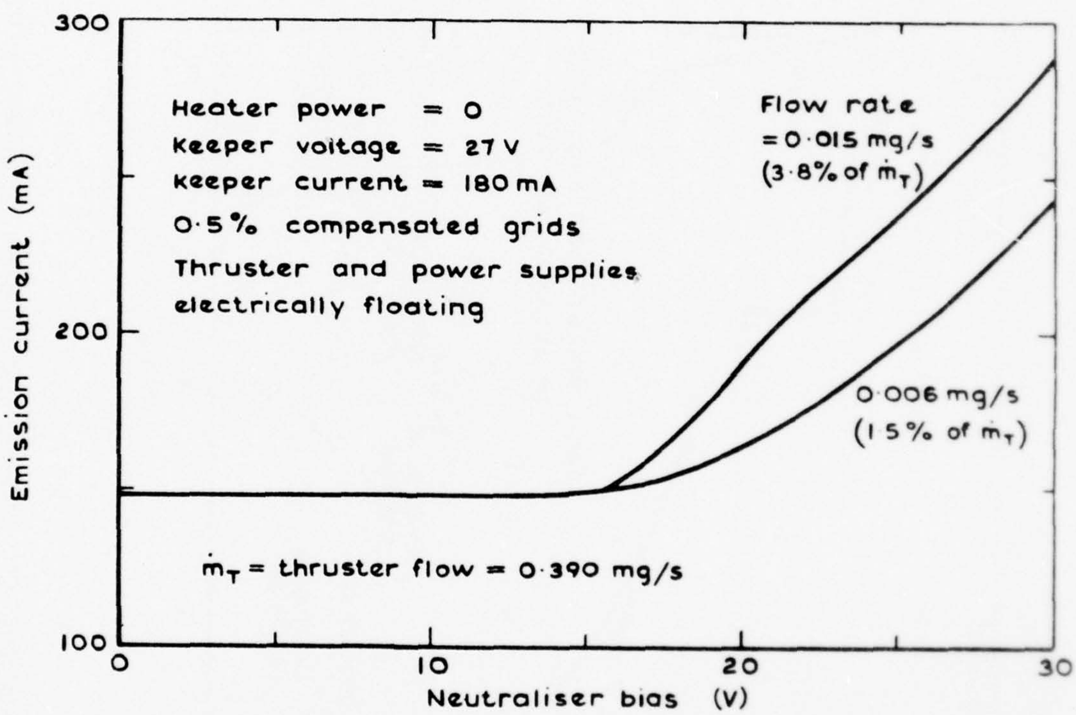

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Fig. 25 Neutraliser voltage-current characteristics prior to the second 1000 hour life-test

Fig. 26

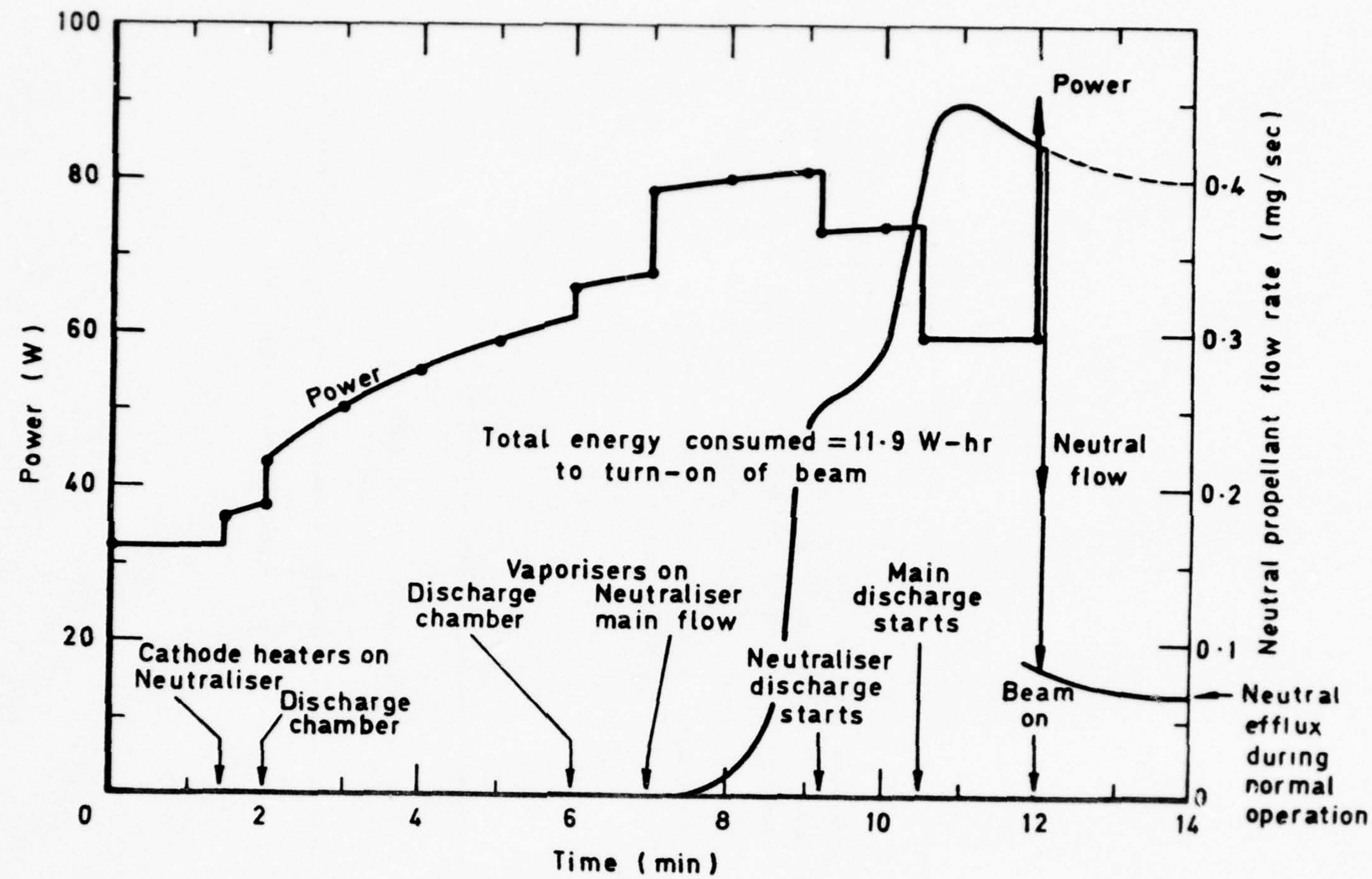


Fig.26 Variation of power input and neutral propellant flow during 12 min starting sequence

TR 77063

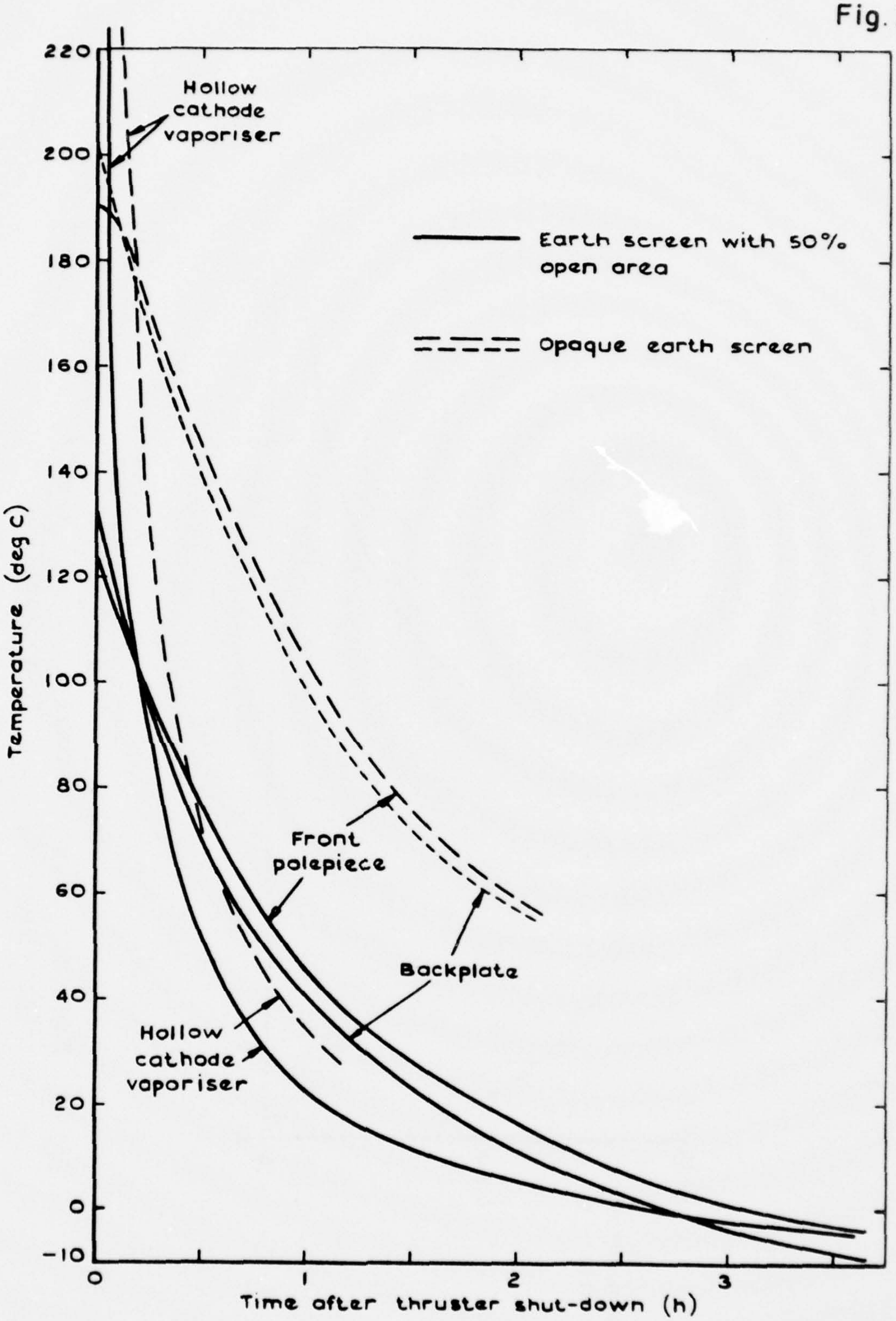


Fig. 27 Thruster cooling curves for (a) perforated earth screen and (b) opaque earth screen

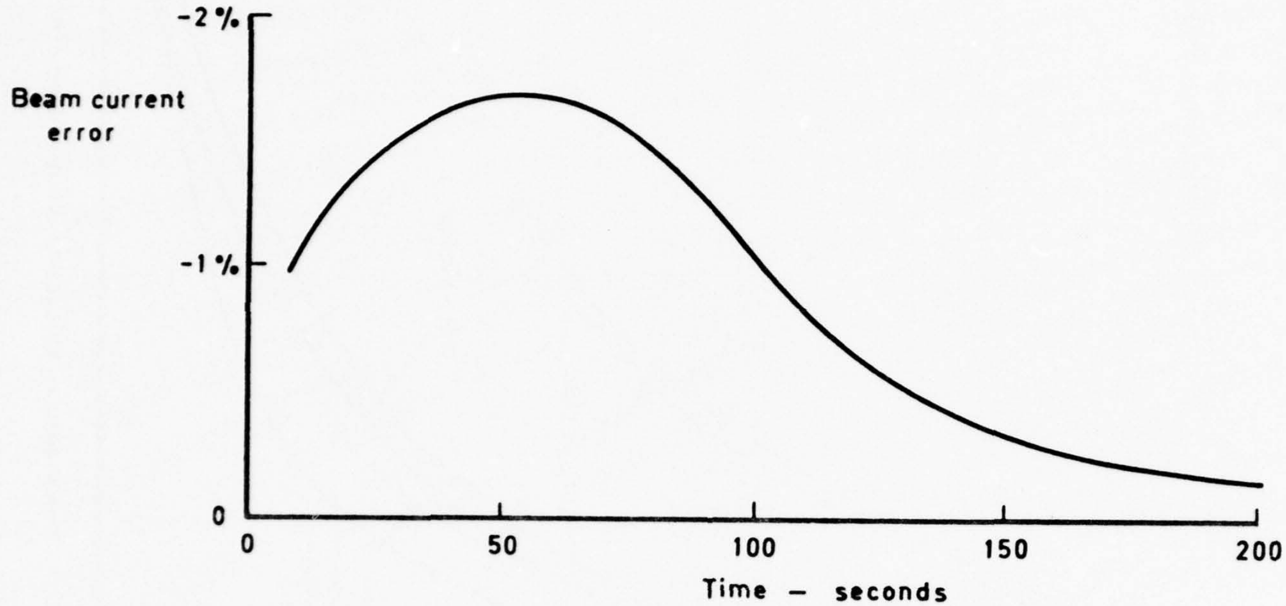
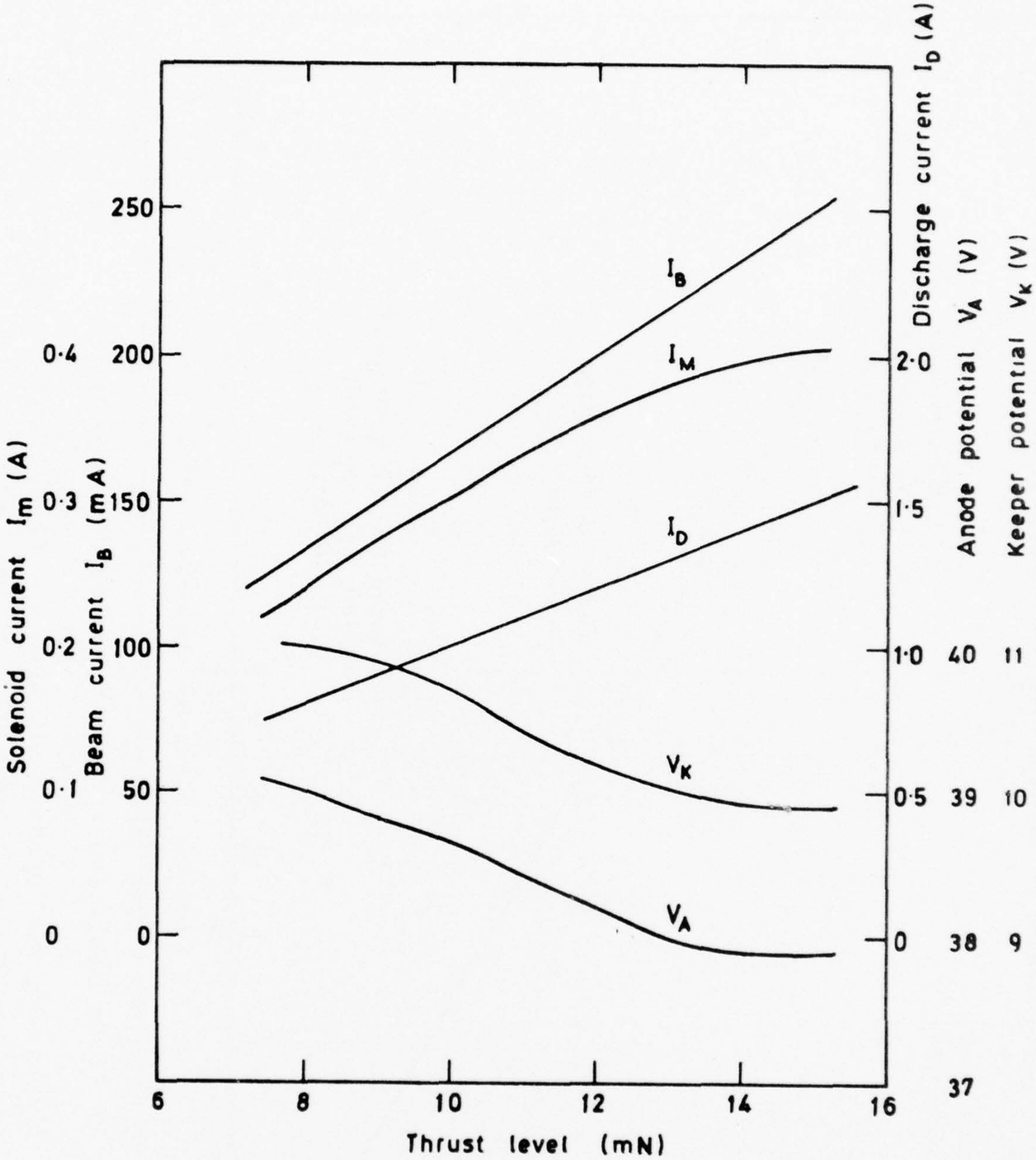


Fig 28 Response of beam current control loop to a 30 second interruption in main flow vaporiser current



$\Delta V = 28V$

$\eta_m \approx 85\%$ at 250 eV/ion

Fig. 29 Thruster parameters as a function of thrust in the thrust range 7-16 mN

Fig. 30

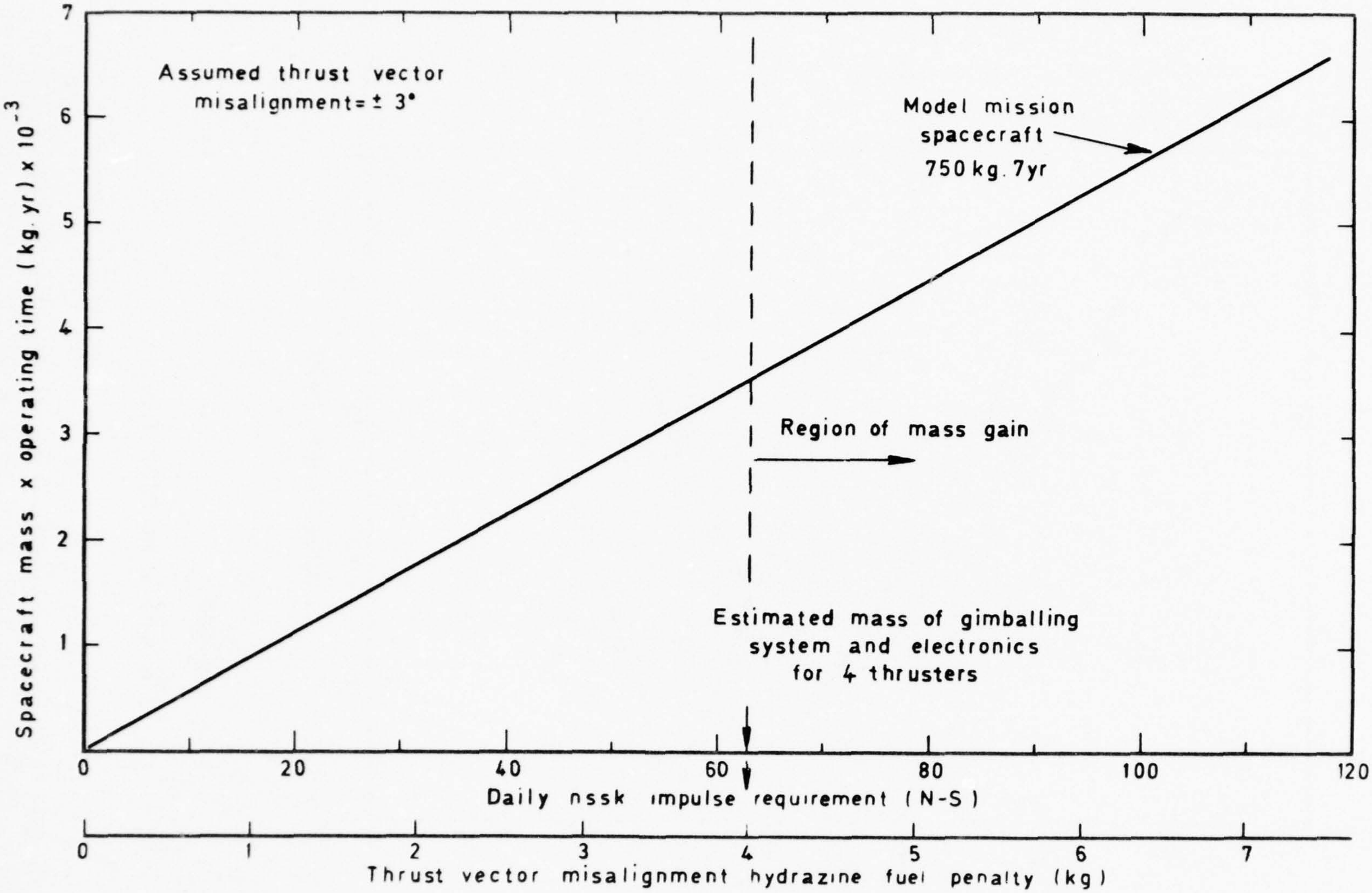


Fig. 30 Hydrazine fuel consumption due to thrust vector misalignment as a function of spacecraft mass x operating time

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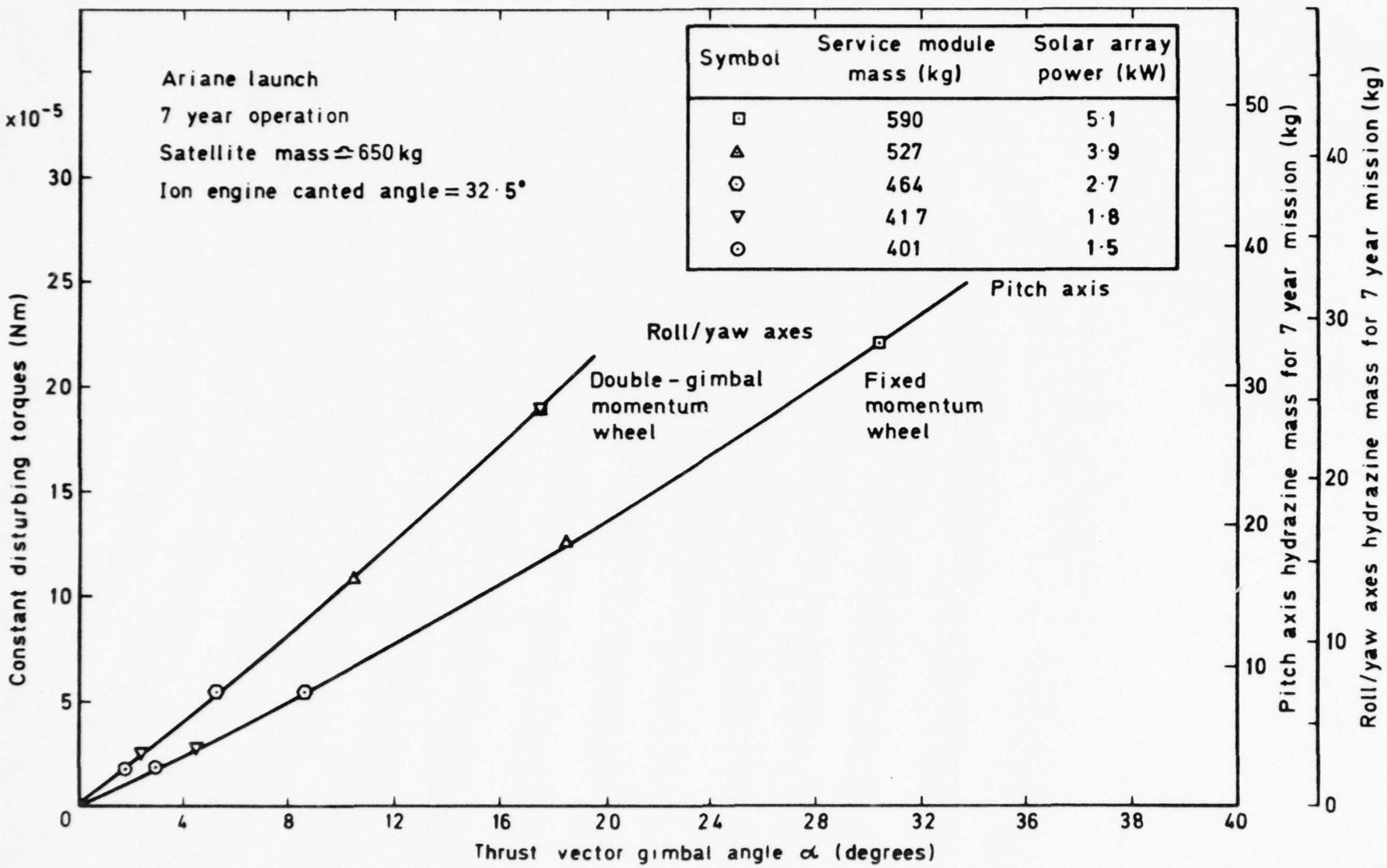

Fig. 31 Thrust vector angle required as a function of disturbing torques for momentum wheel offloading

Fig. 32

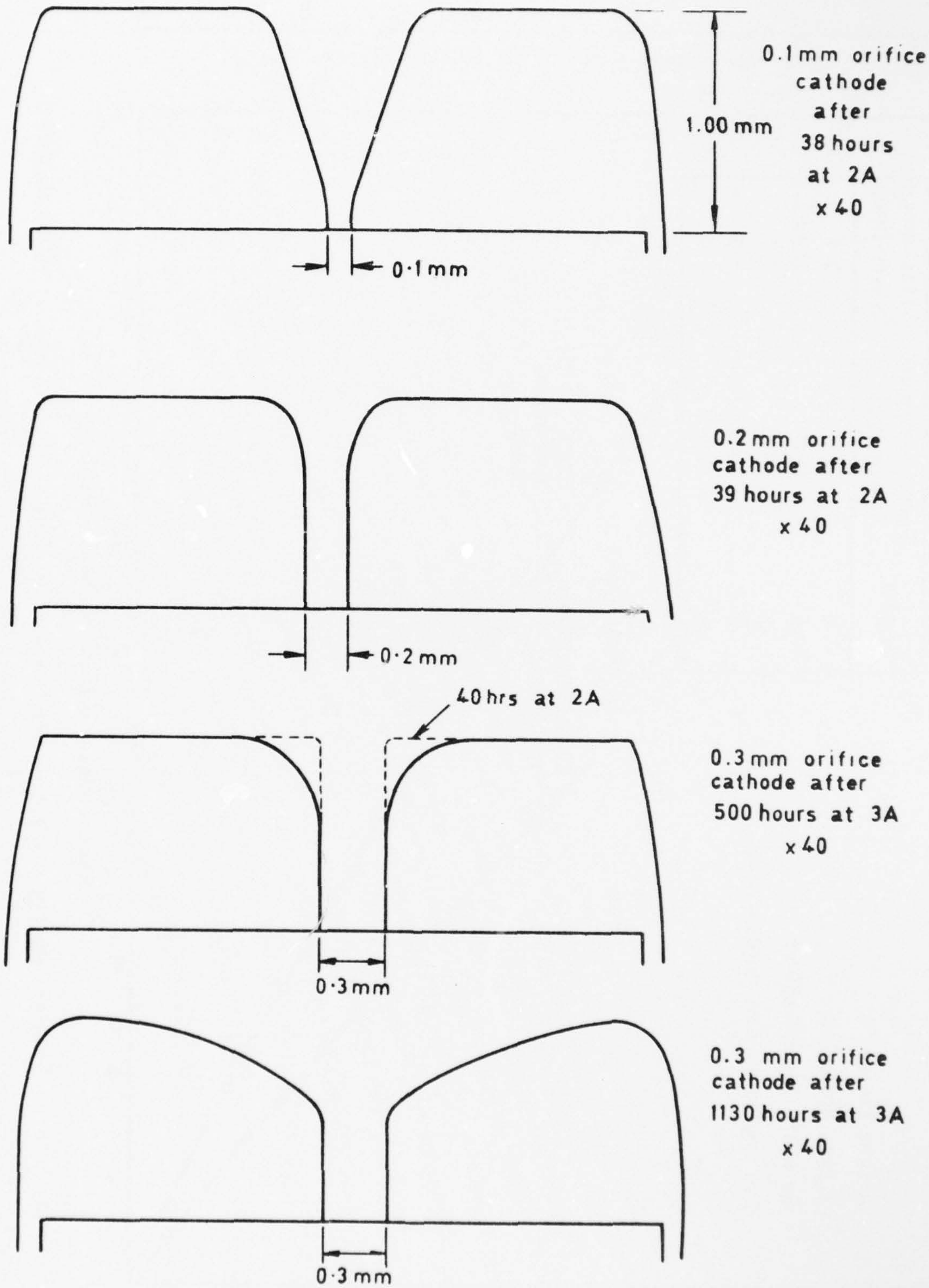

Fig. 32 Sections through cathode tips after life testing

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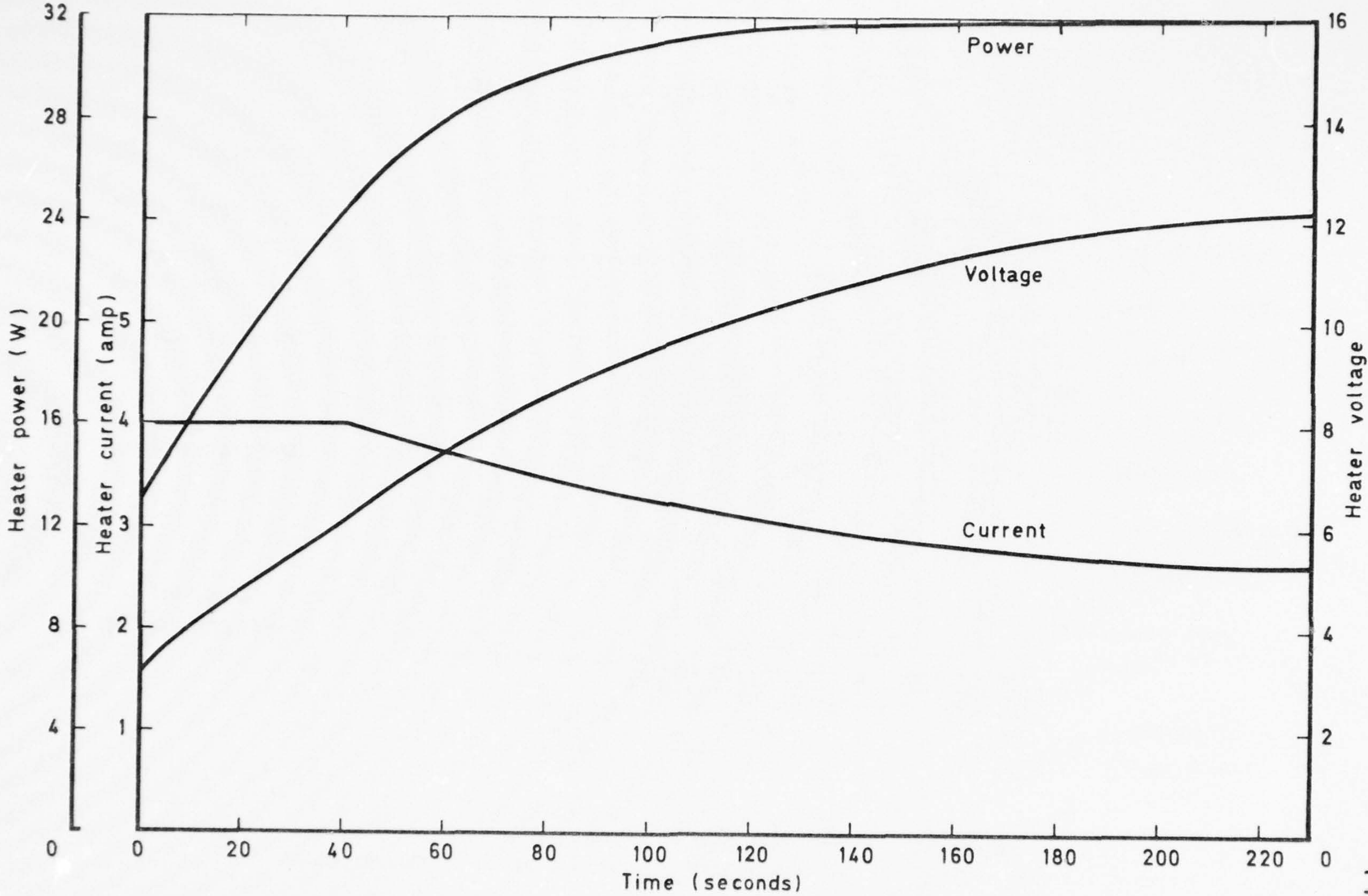

Fig. 33 Power, current and voltage profiles used in cathode heater cycling test

Fig.33

Fig. 34

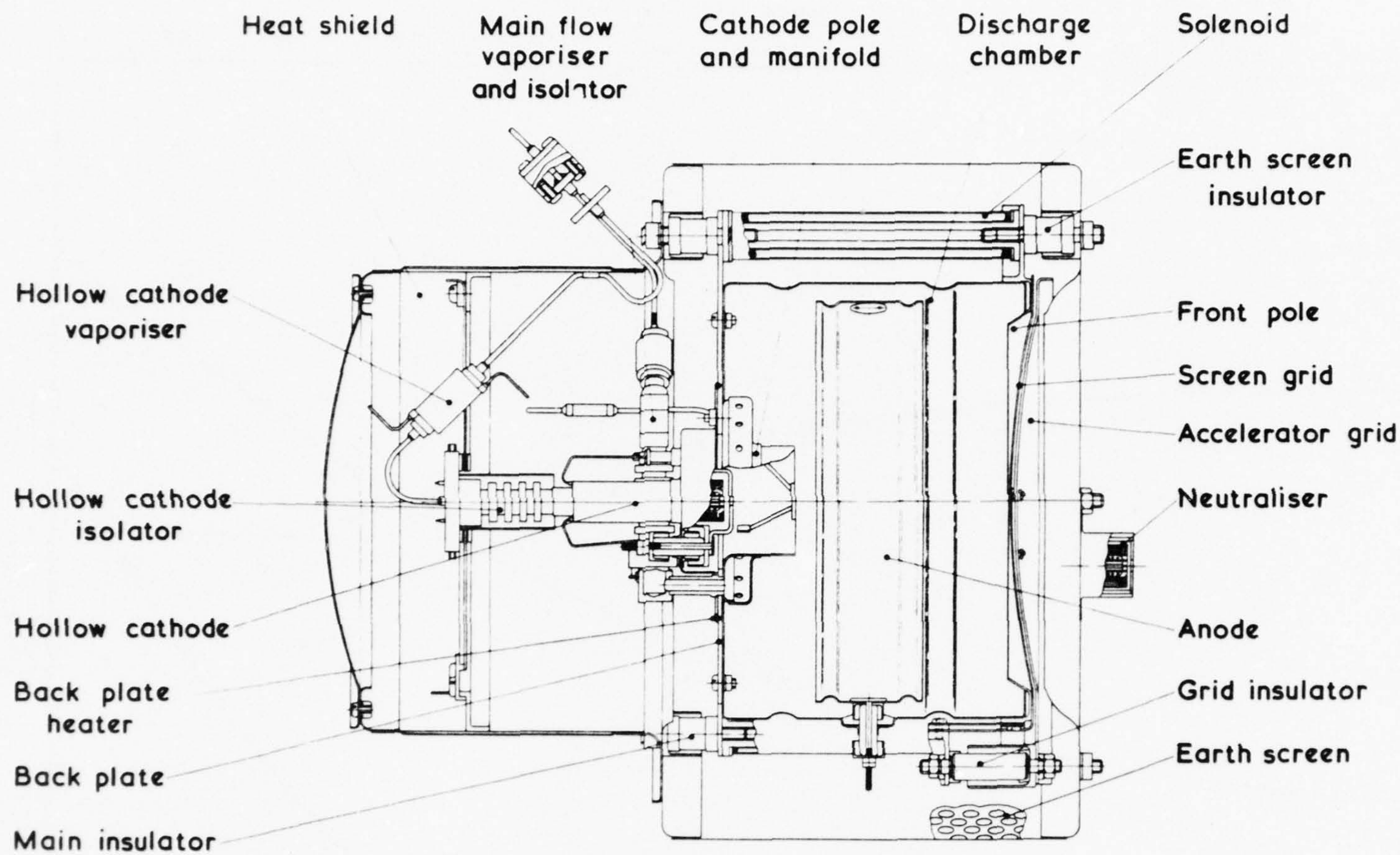

Fig. 34 T5 Thruster

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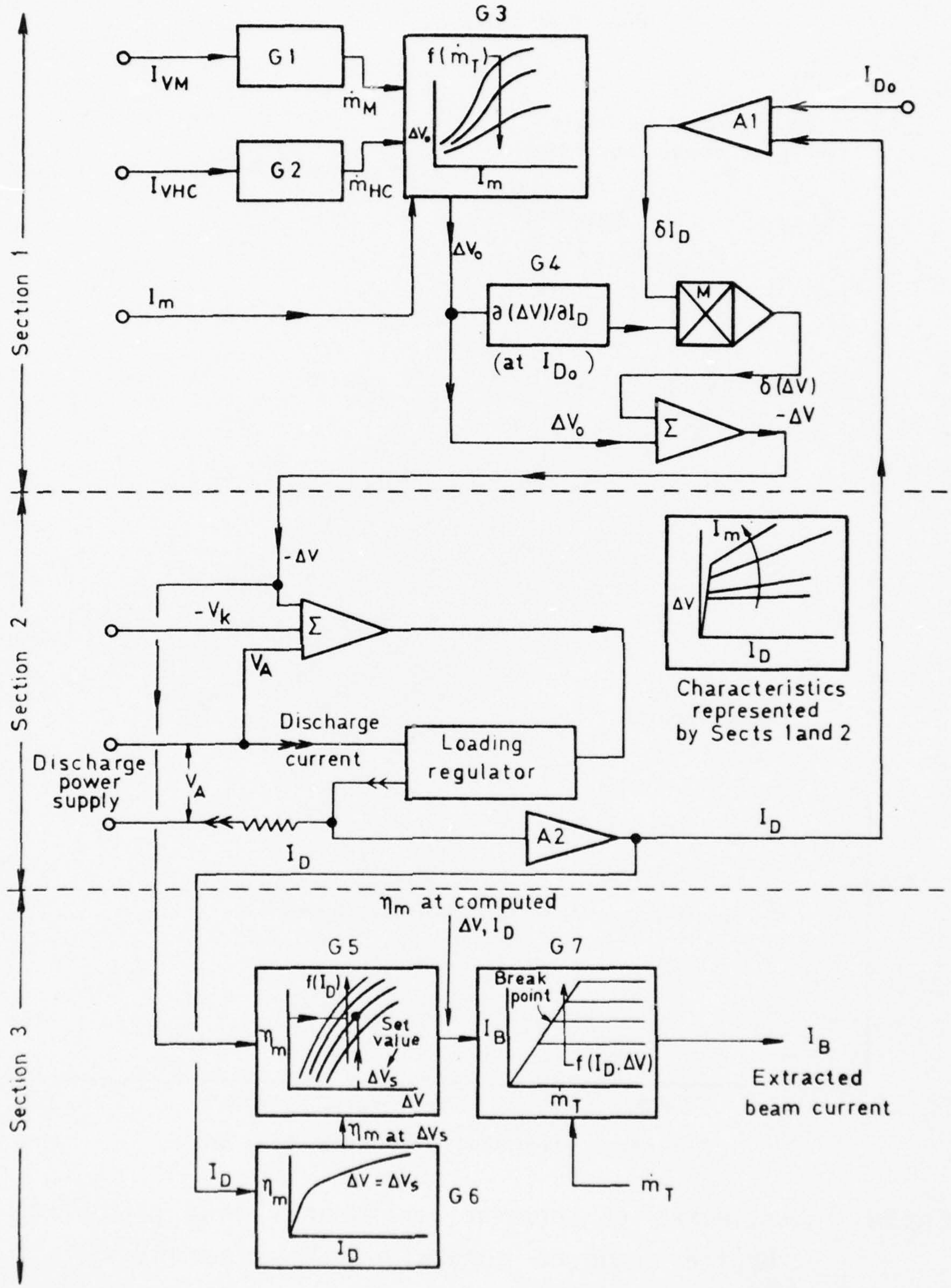

Fig.35 Schematic of thruster simulator

Fig. 36

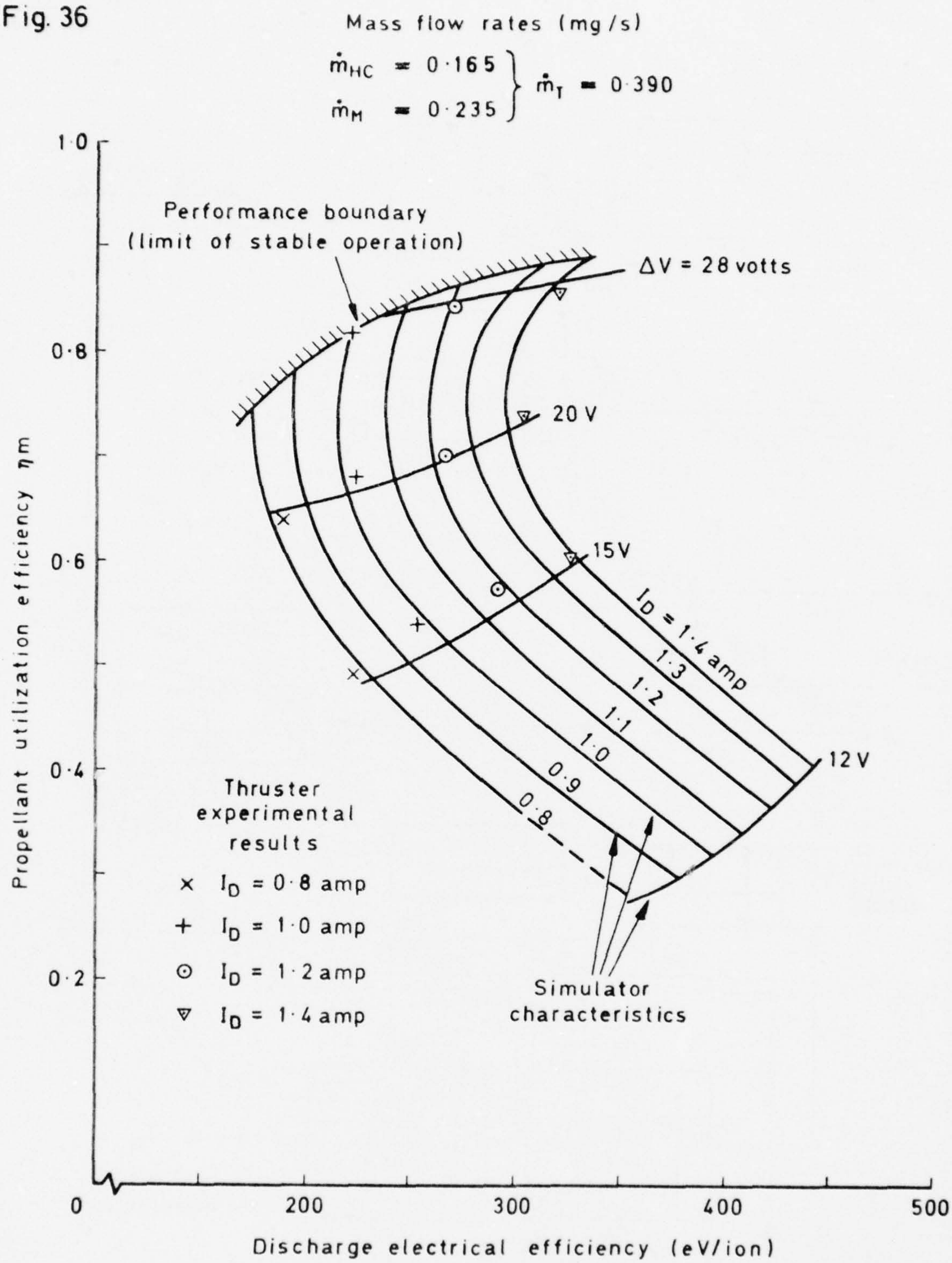

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Fig. 36 Comparison of thruster performance map predicted by the analogue simulator with experimental measurements, for early version of T4 thruster

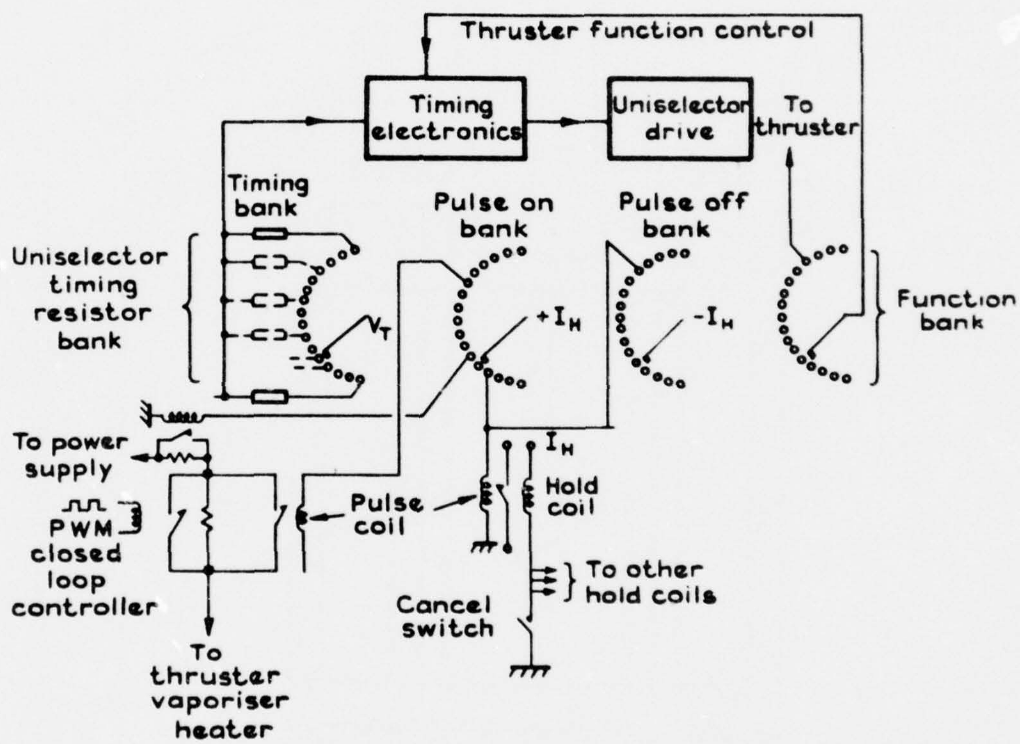

Fig. 37 Schematic of electromechanical sequencer

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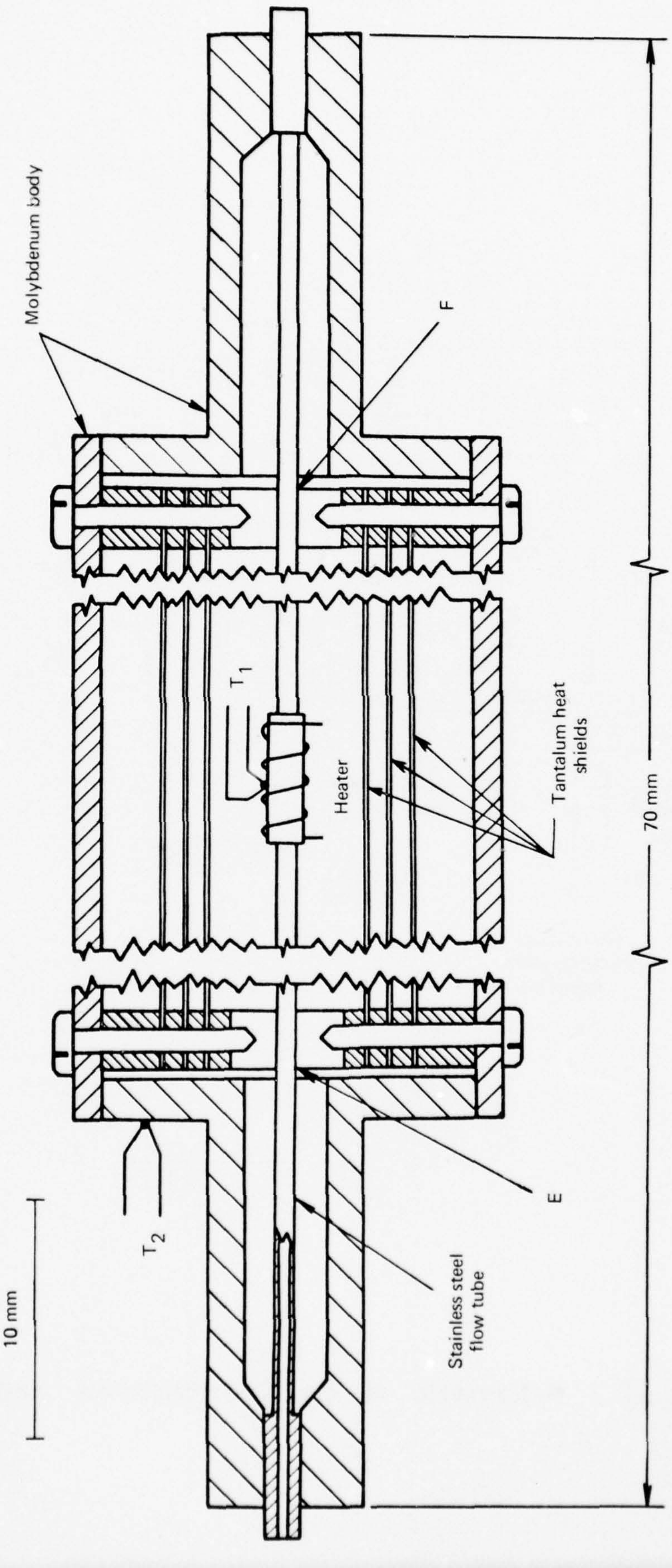
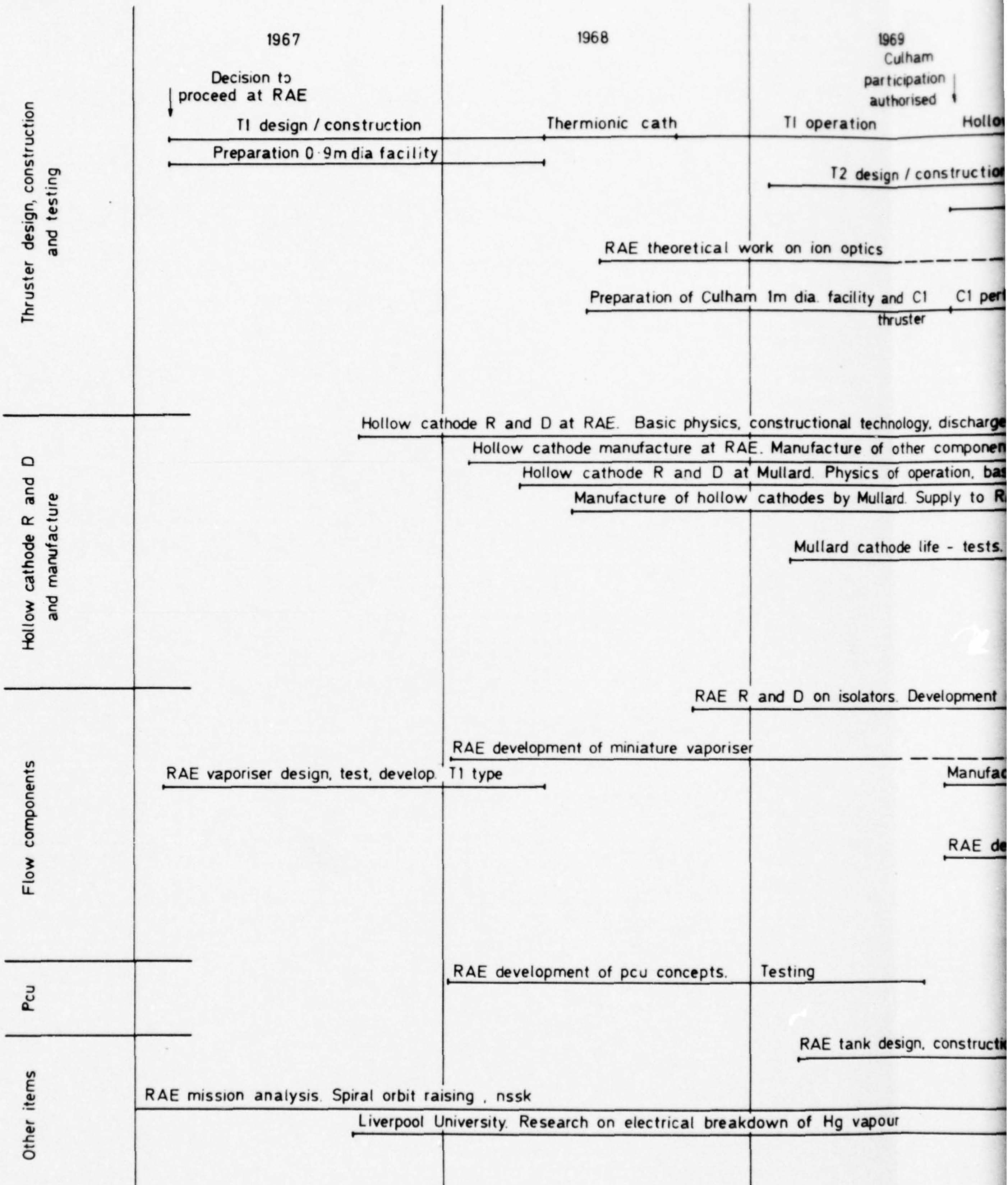


Fig 38 Section through experimental flowmeter



1967
1968
1969
Decision to proceed at RAE
Culham participation authorised
Thruster design, construction and testing
T1 design / construction
Thermionic cath
T1 operation
Hollo
Preparation 0·9m dia facility
T2 design / constructio
RAE theoretical work on ion optics
Preparation of Culham 1m dia. facility and C1 thruster
C1 perf
Hollow cathode R and D and manufacture
Hollow cathode R and D at RAE. Basic physics, constructional technology, discharge
Hollow cathode manufacture at RAE. Manufacture of other componen
Hollow cathode R and D at Mullard. Physics of operation, bas
Manufacture of hollow cathodes by Mullard. Supply to R
Mullard cathode life - tests.
Flow components
RAE R and D on isolators. Development
RAE development of miniature vaporiser
RAE vaporiser design, test, develop. T1 type
Manufac
RAE de
Pcu
RAE development of pcu concepts.
Testing
Other items
RAE tank design, constructi
RAE mission analysis. Spiral orbit raising , nssk
Liverpool University. Research on electrical breakdown of Hg vapour

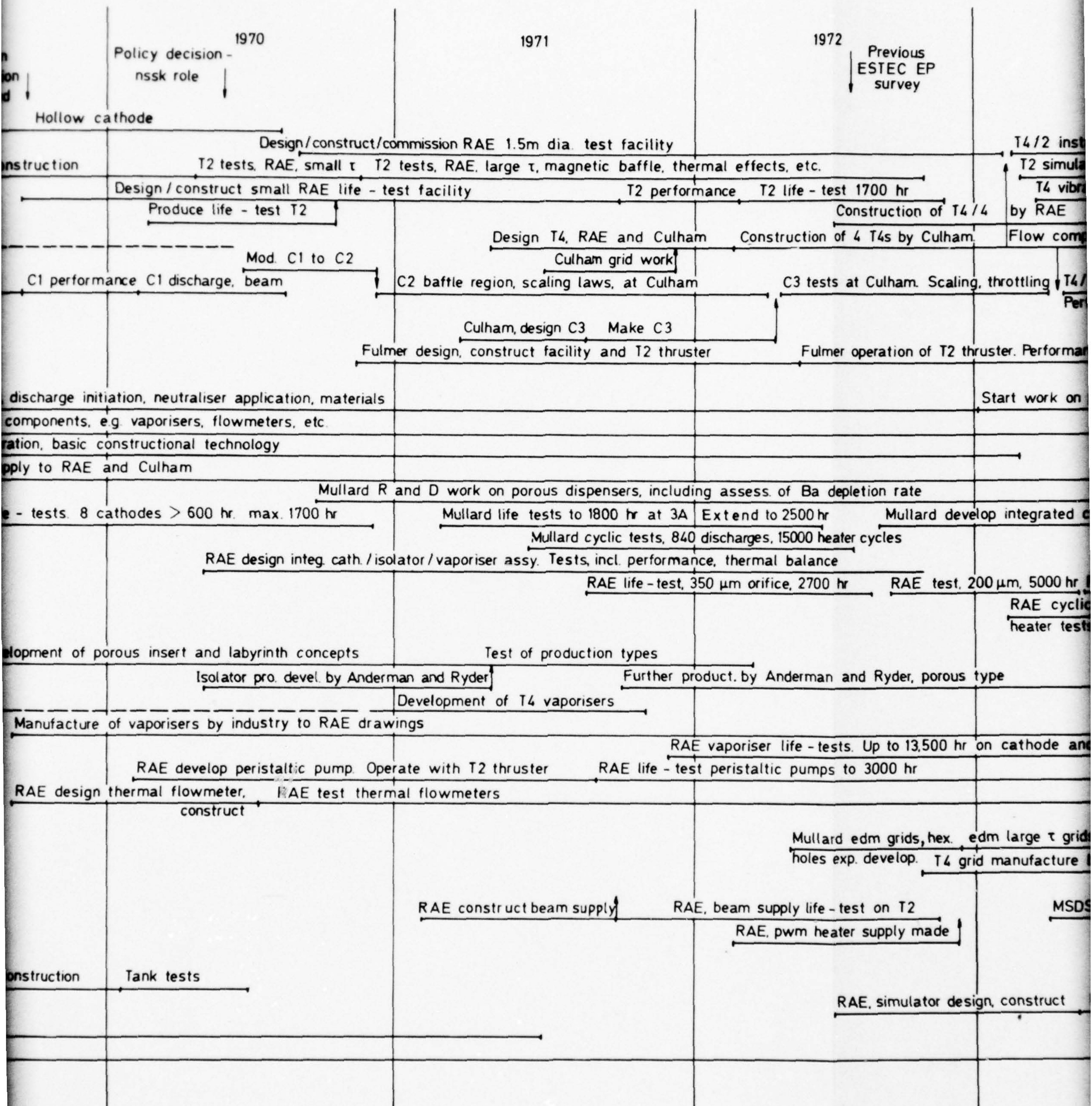
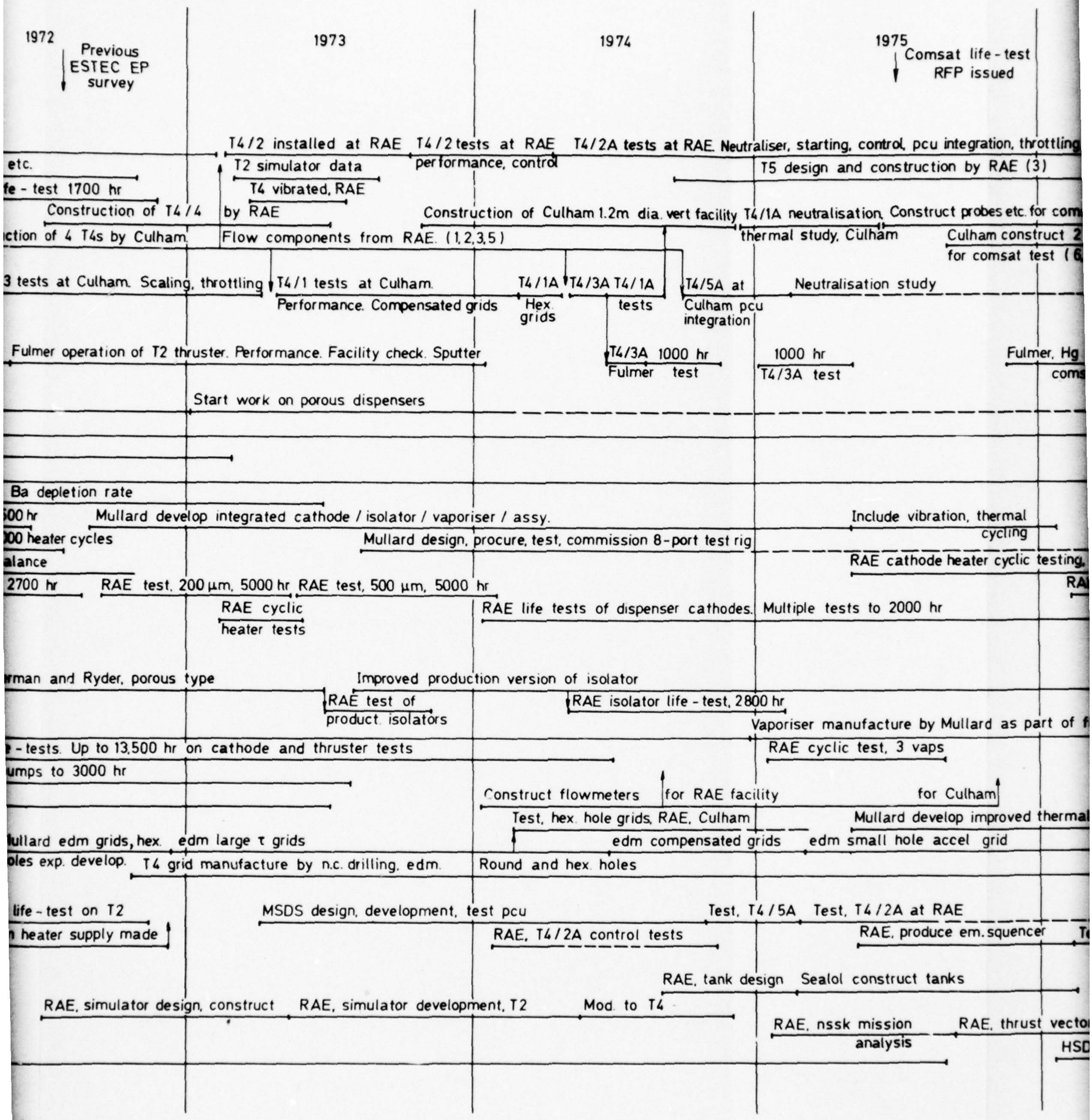


Fig. 39 Bar chart showing development of the UK 10cm ion thruster to 1976

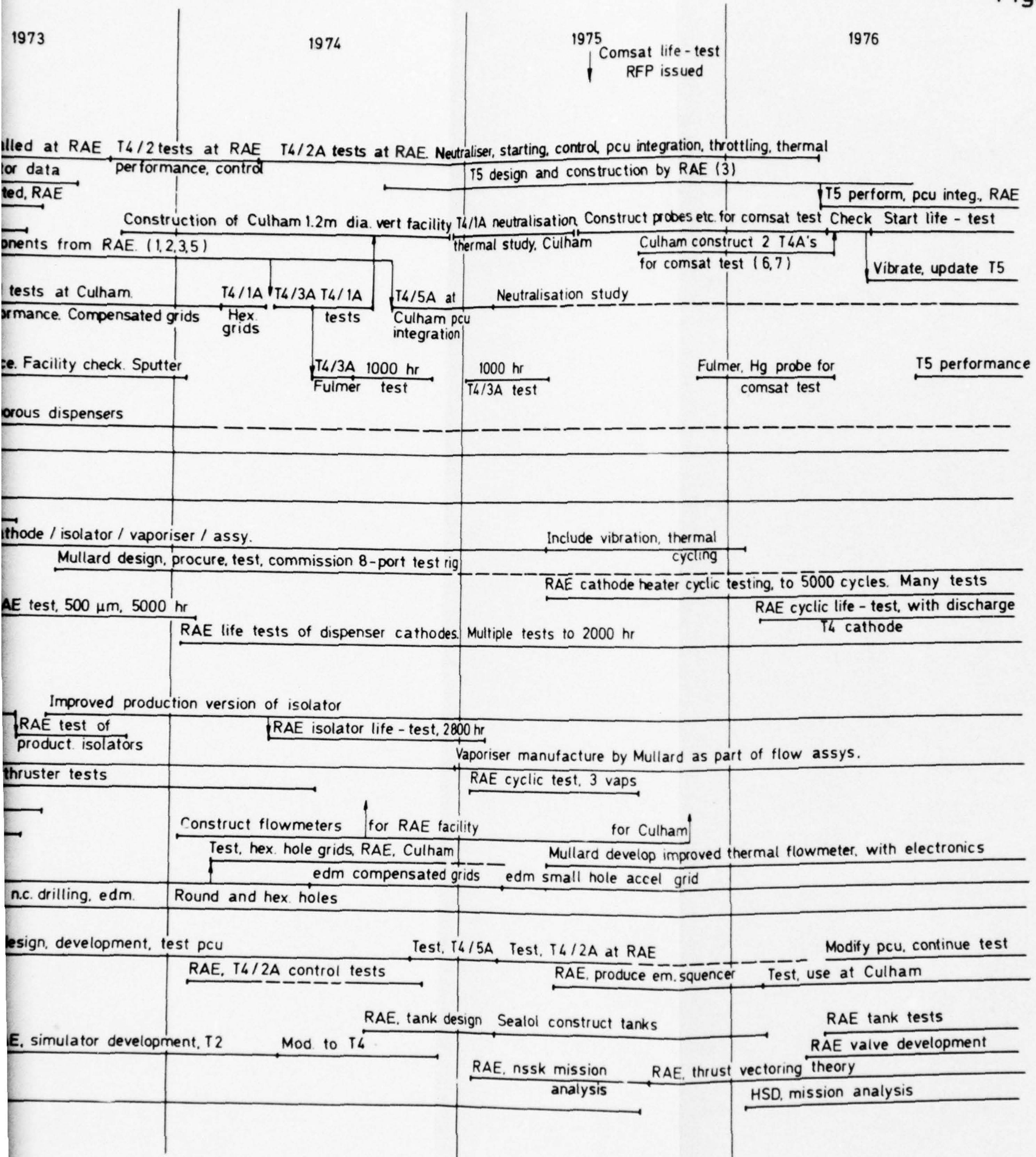
2



cm ion thruster to 1976

3

Fig.39


1973
1974
1975
1976
Comsat life - test RFP issued
lled at RAE
T4/2 tests at RAE
T4/2A tests at RAE
Neutraliser, starting, control, pcu integration, throttling, thermal
tor data
performance, control
T5 design and construction by RAE (3)
ted, RAE
T5 perform, pcu integ., RAE
Construction of Culham 1.2m dia. vert facility
T4/1A neutralisation
thermal study, Culham
Construct probes etc. for comsat test
Check
Start life - test
Culham construct 2 T4A's
for comsat test (6,7)
Vibrate, update T5
onents from RAE. (1,2,3,5)
tests at Culham.
rmance. Compensated grids
T4/1A
Hex. grids
T4/3A
T4/1A
tests
T4/5A at
Culham pcu integration
Neutralisation study
ce. Facility check. Sputter
T4/3A
Fulmer
1000 hr
test
1000 hr
T4/3A test
Fulmer, Hg probe for
comsat test
T5 performance
orous dispensers
thode / isolator / vaporiser / assy.
Include vibration, thermal
cycling
Mullard design, procure, test, commission 8-port test rig
RAE cathode heater cyclic testing, to 5000 cycles. Many tests
AE test, 500 μm, 5000 hr
RAE cyclic life - test, with discharge
T4 cathode
RAE life tests of dispenser cathodes. Multiple tests to 2000 hr
Improved production version of isolator
RAE test of
product. isolators
RAE isolator life - test, 2800 hr
Vaporiser manufacture by Mullard as part of flow assys.
thruster tests
RAE cyclic test, 3 vaps
Construct flowmeters
for RAE facility
for Culham
Test, hex. hole grids, RAE, Culham
Mullard develop improved thermal flowmeter, with electronics
edm compensated grids
edm small hole accel grid
n.c. drilling, edm.
Round and hex. holes
esign, development, test pcu
Test, T4/5A
Test, T4/2A at RAE
Modify pcu, continue test
RAE, T4/2A control tests
RAE, produce em. squencer
Test, use at Culham
RAE, tank design
Sealol construct tanks
RAE tank tests
E, simulator development, T2
Mod. to T4
RAE valve development
RAE, nssk mission
analysis
RAE, thrust vectoring theory
HSD, mission analysis

3

4

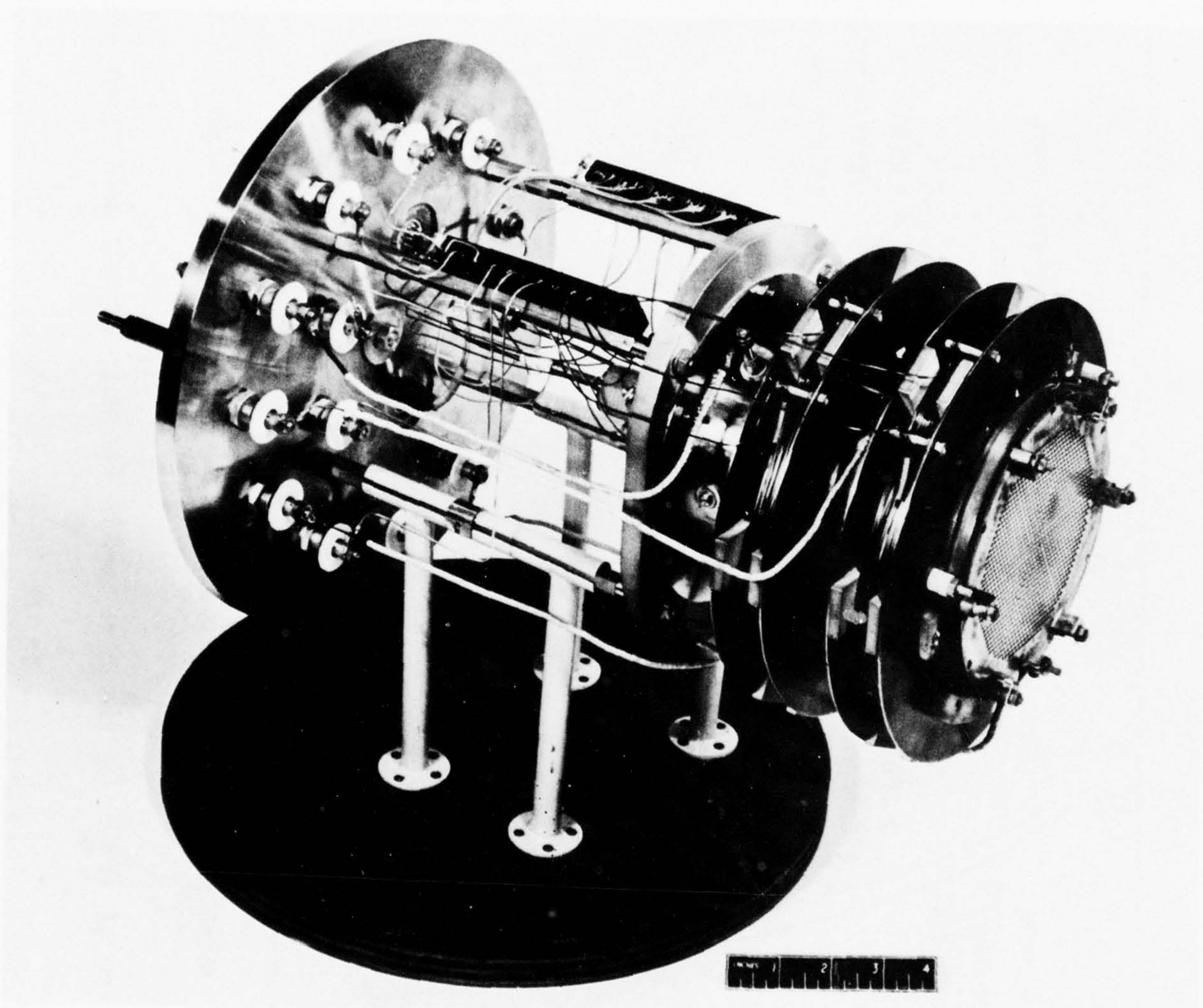


Fig 40 RAE T1 thruster of 1967/68

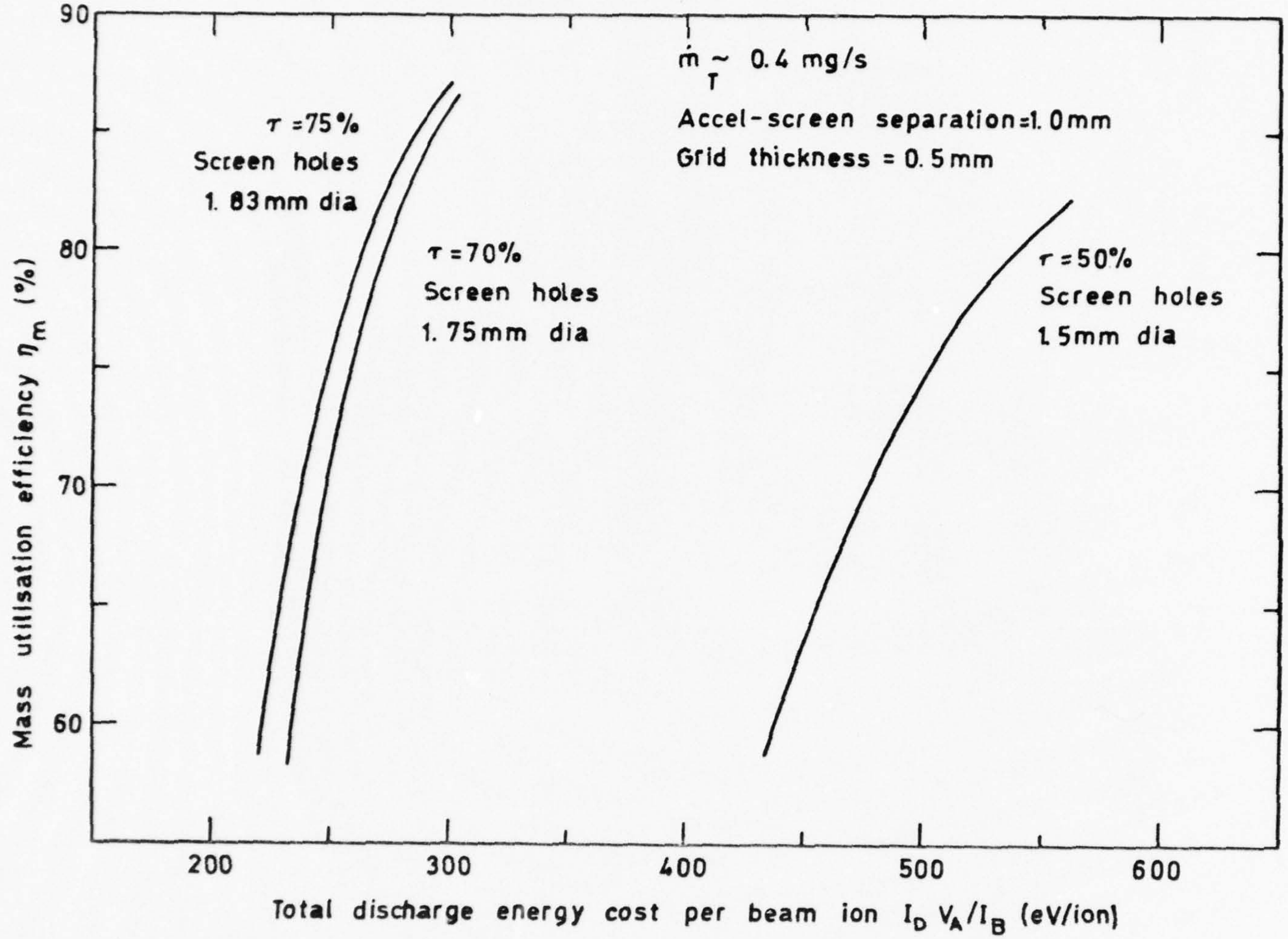


Fig. 41 Performance of RAE T2 thruster with various screen grid open area ratios

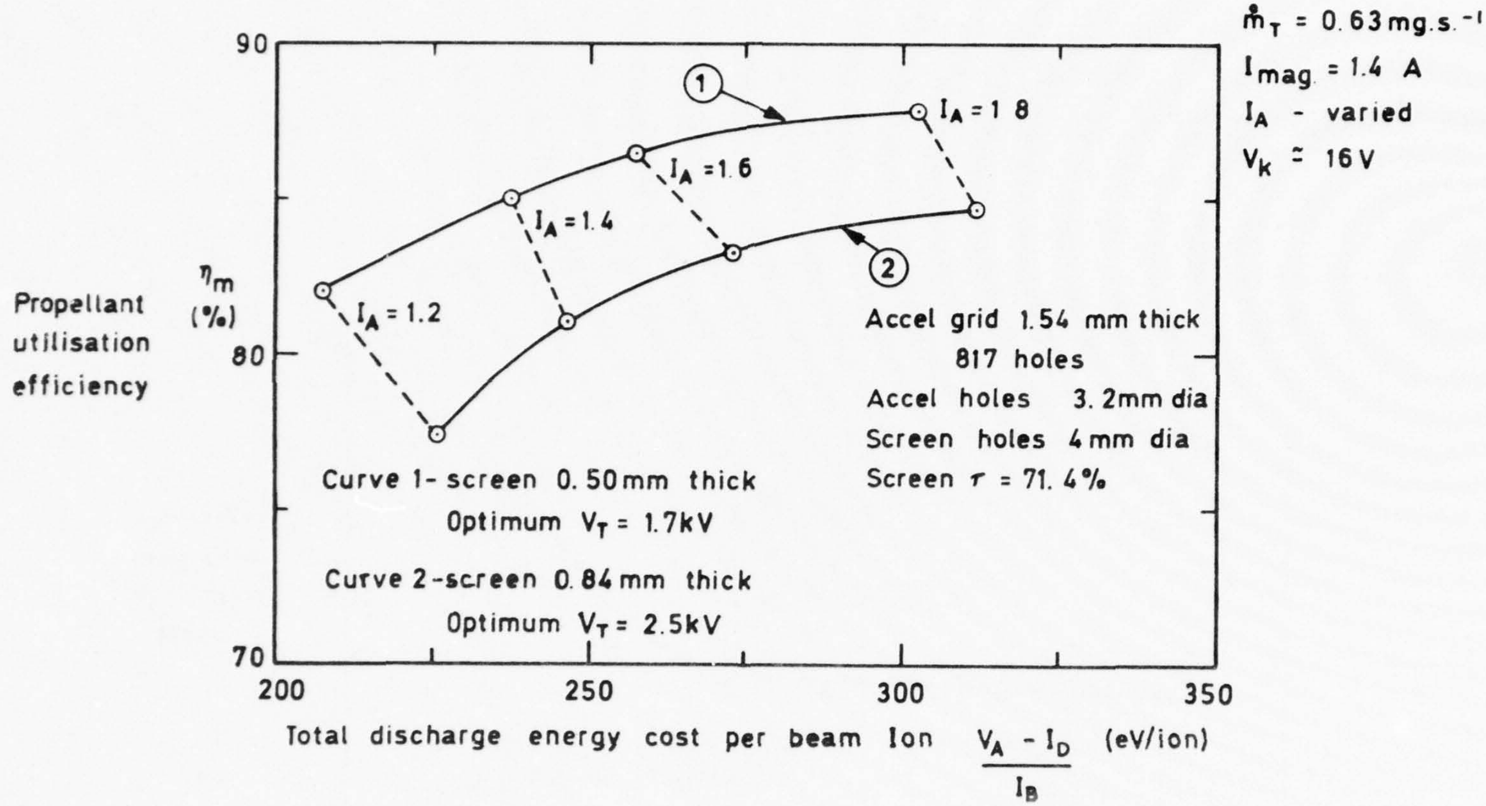


Fig. 42 Influence of screen grid thickness on performance of Culham C1 thruster

Fig. 42

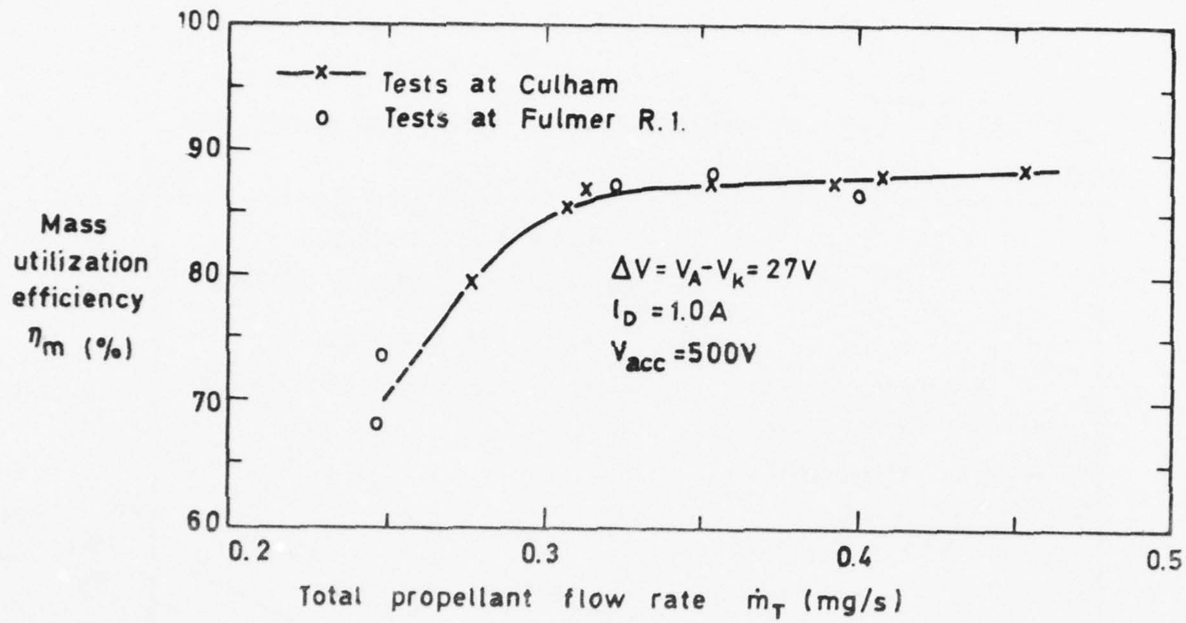


Fig. 43 Comparison between performance data obtained at Culham laboratory and Fulmer R.I. from the same T4A thruster

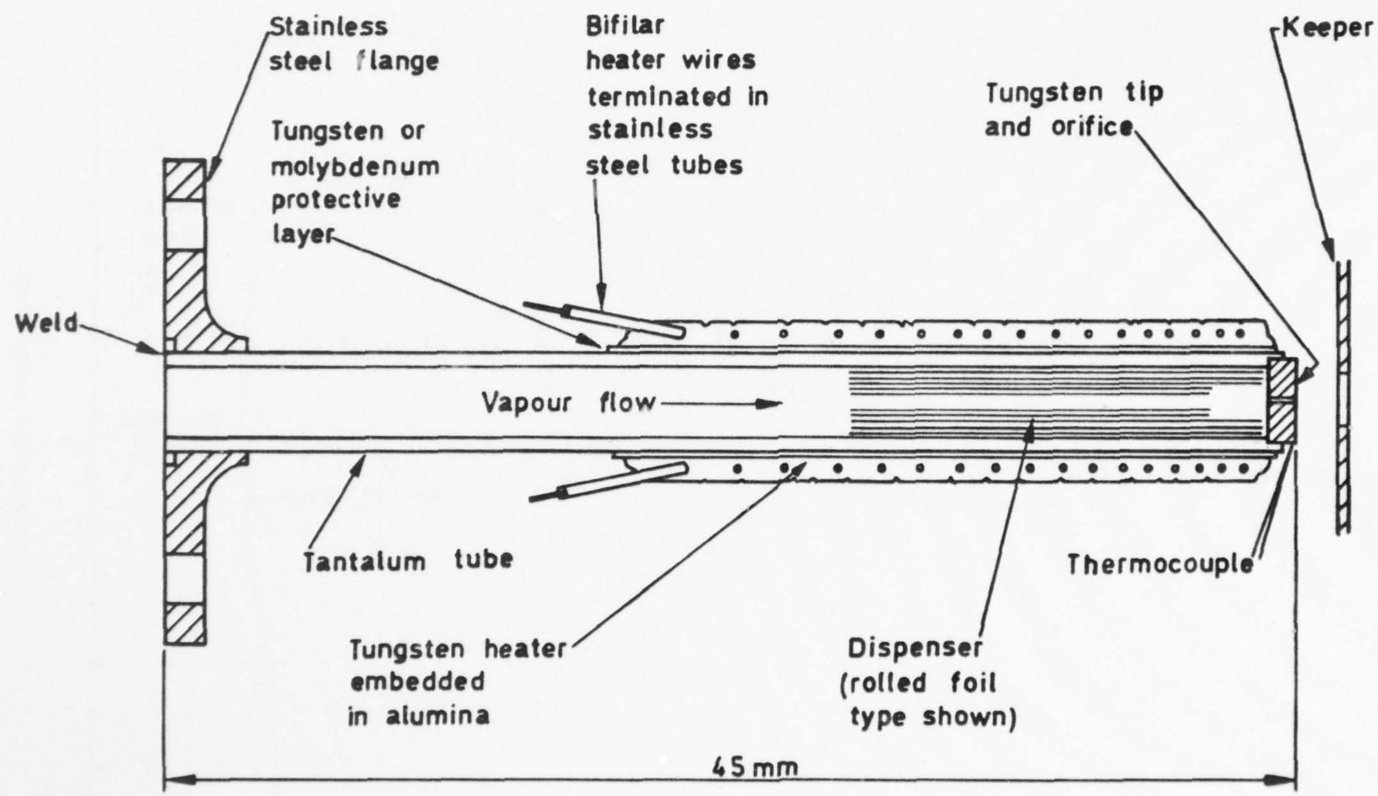


Fig. 44 RAE laboratory-type hollow cathode used for physical investigations and early life tests

Fig. 45

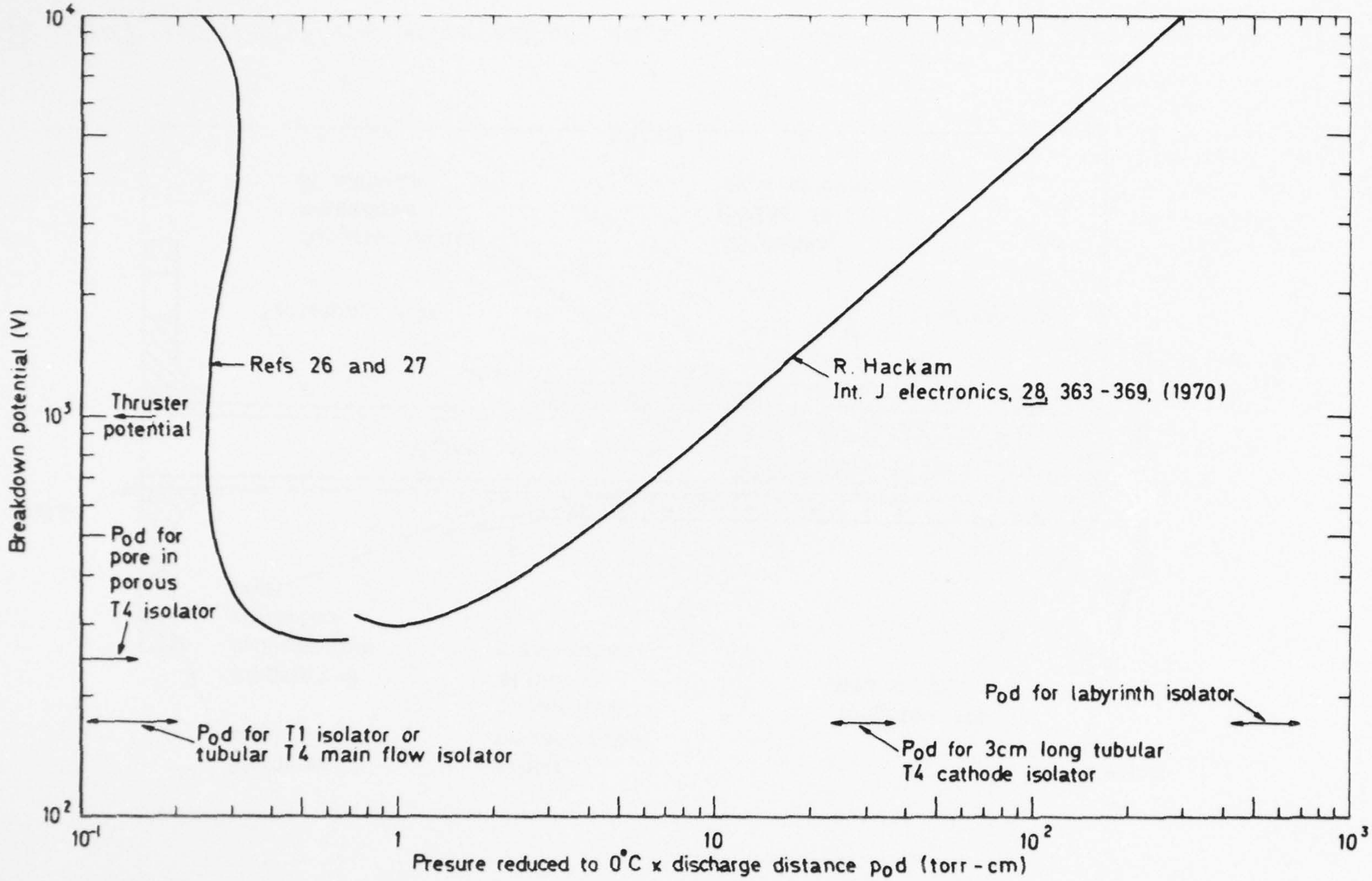


Fig. 45 Paschen curve for mercury vapour

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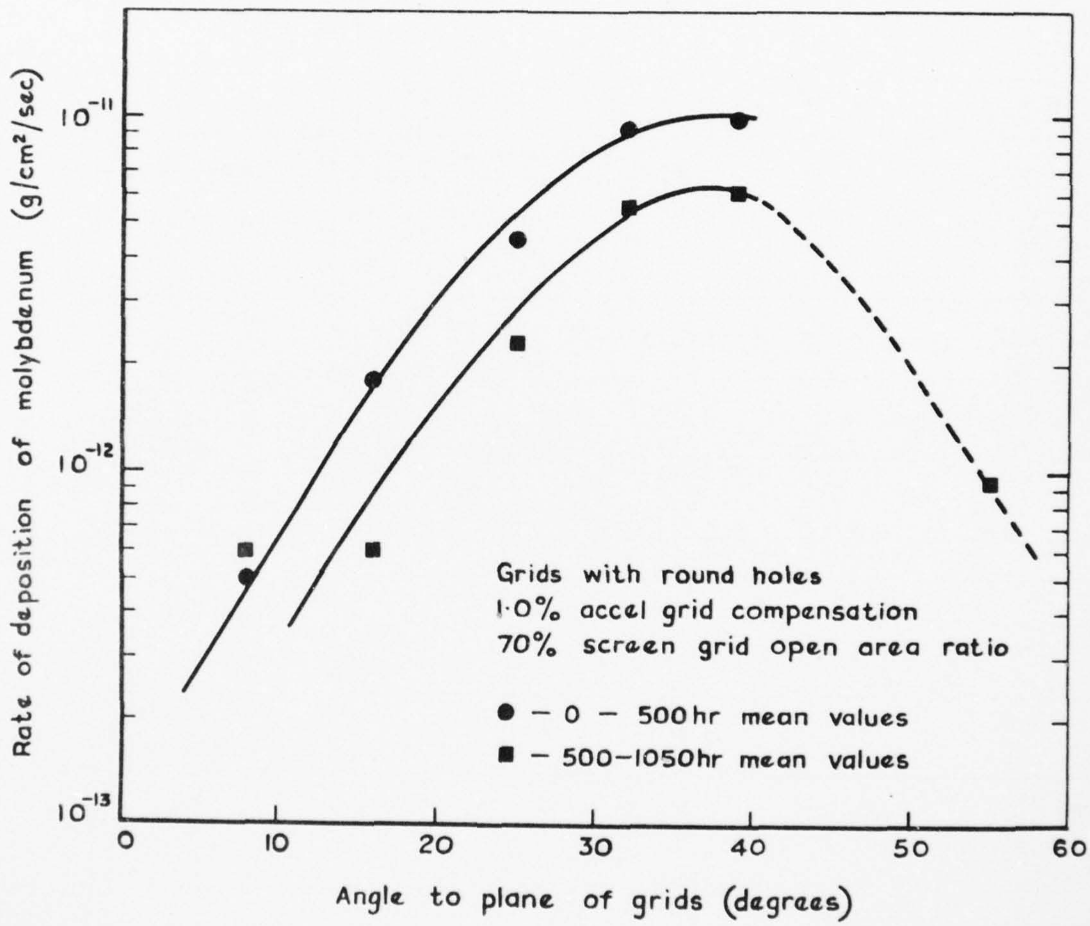


Fig. 46 Deposition rate of molybdenum sputtered from the accel grid as a function of angle during the first 1000 hr life-test

Fig. 47

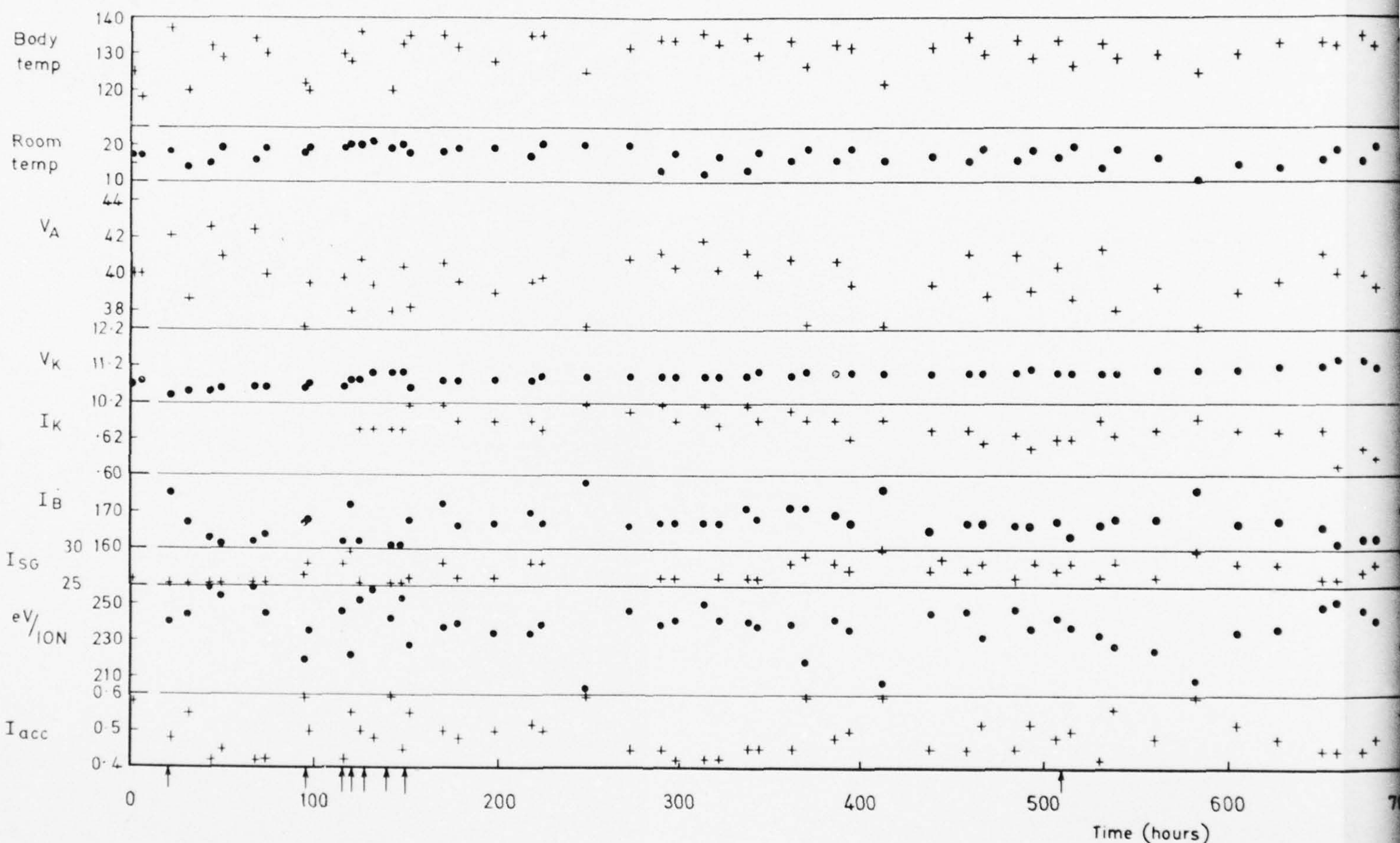
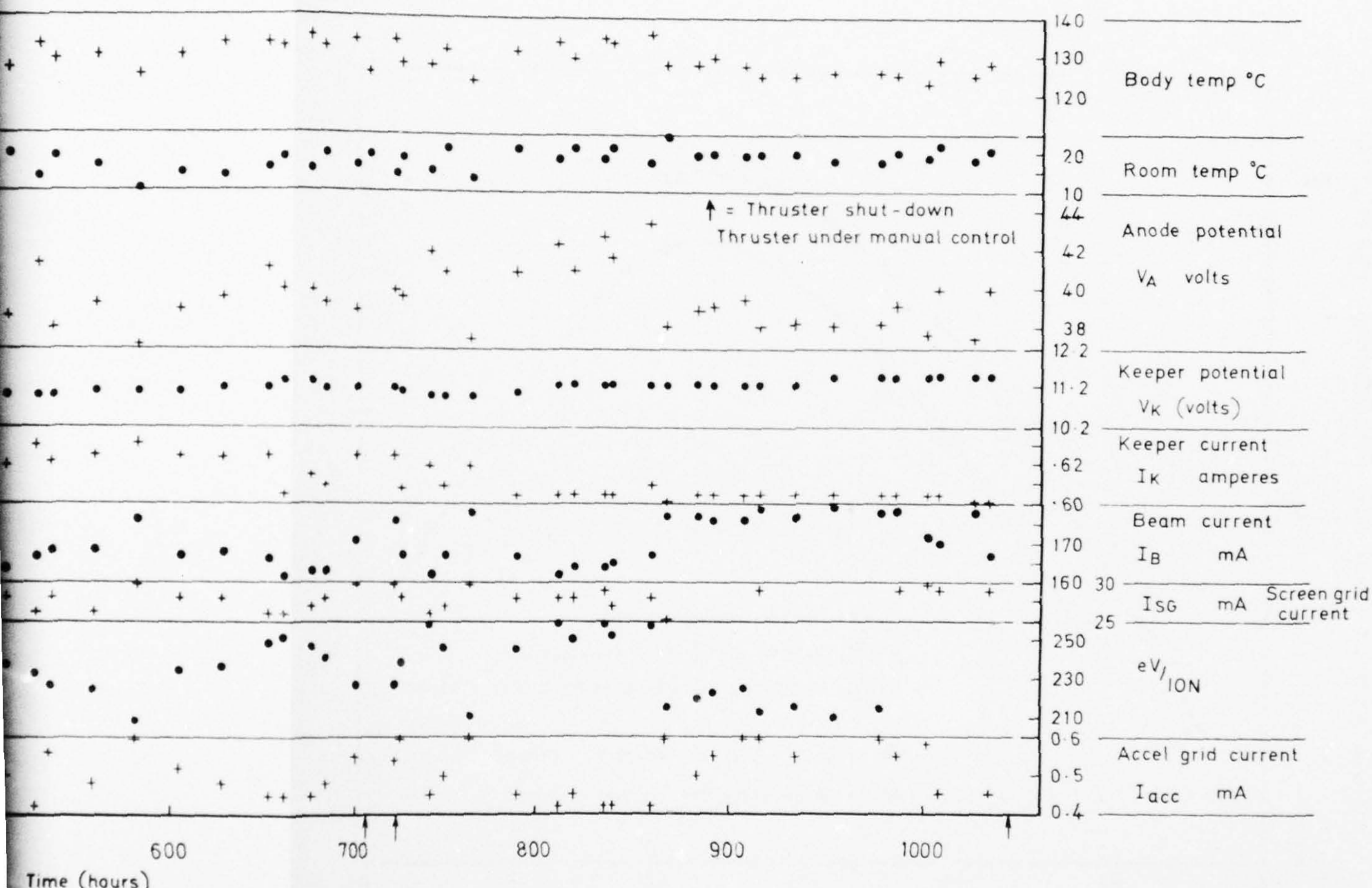


Fig. 47 Thruster parameters as a function of time througho



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ction of time throughout the second 1000 h life-test

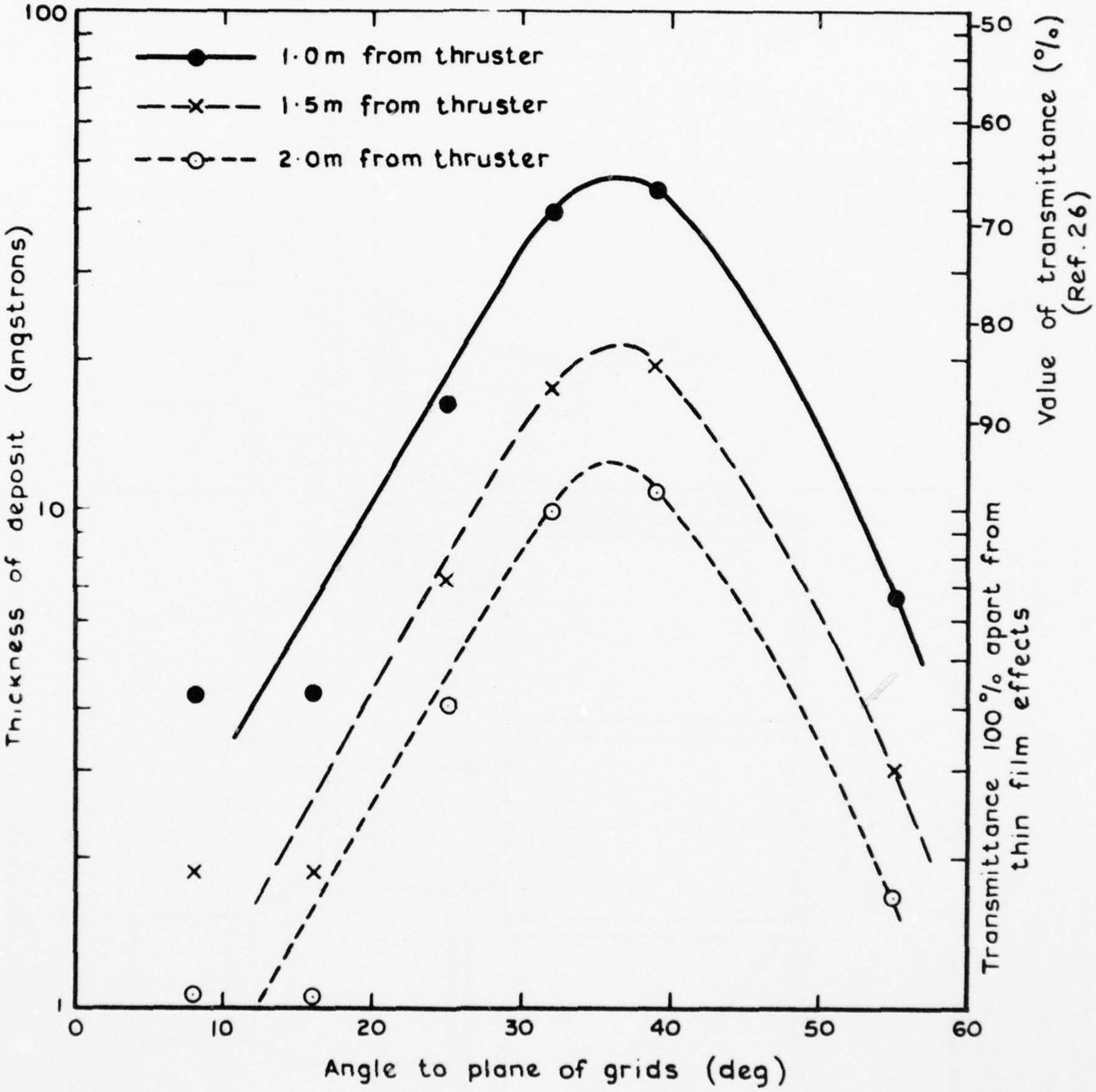

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Fig. 48 Deposition rate of sputtered material as a function of angle at various distances from the thruster

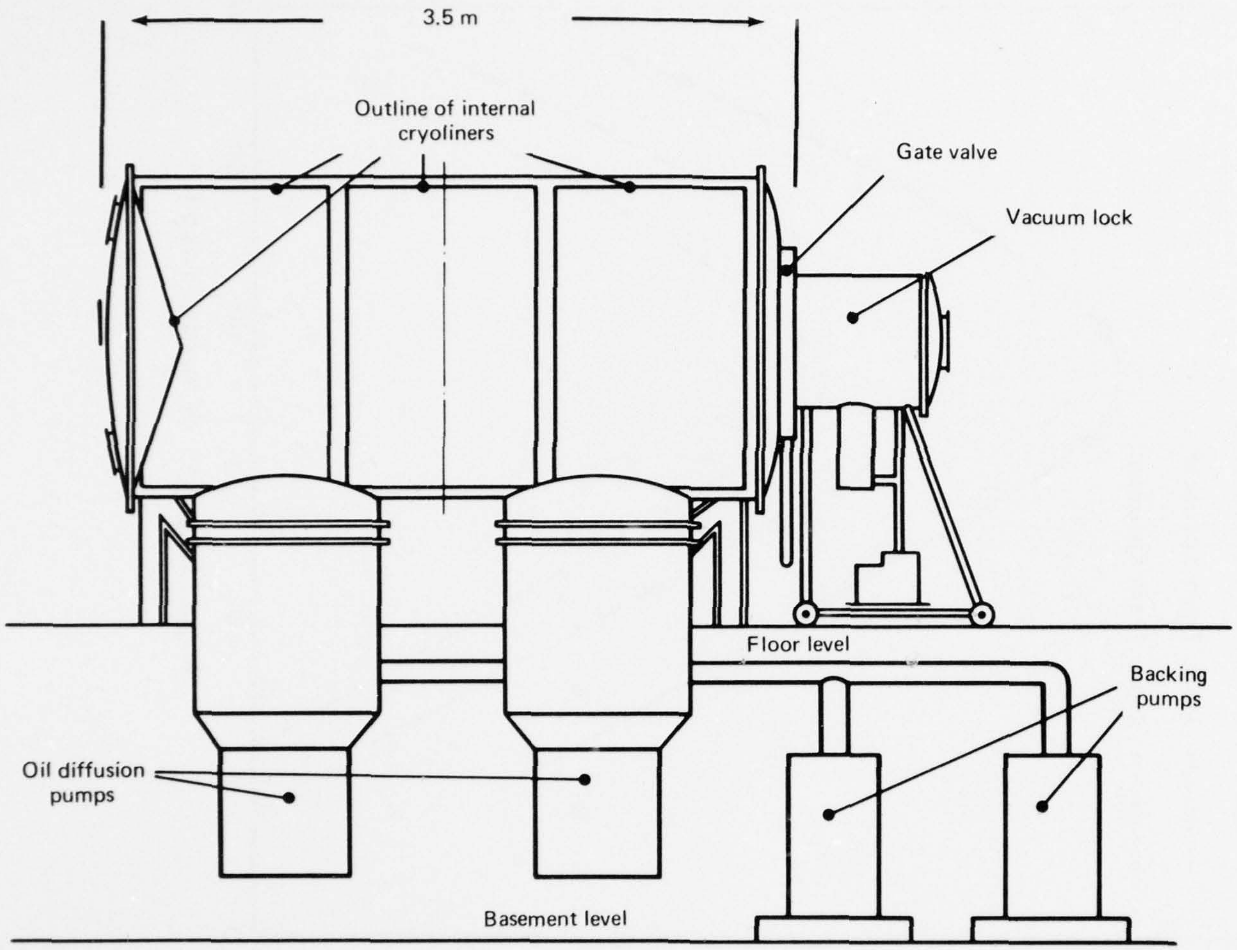

Fig 49 **Schematic diagram of RAE 1.5m ion thruster test chamber**

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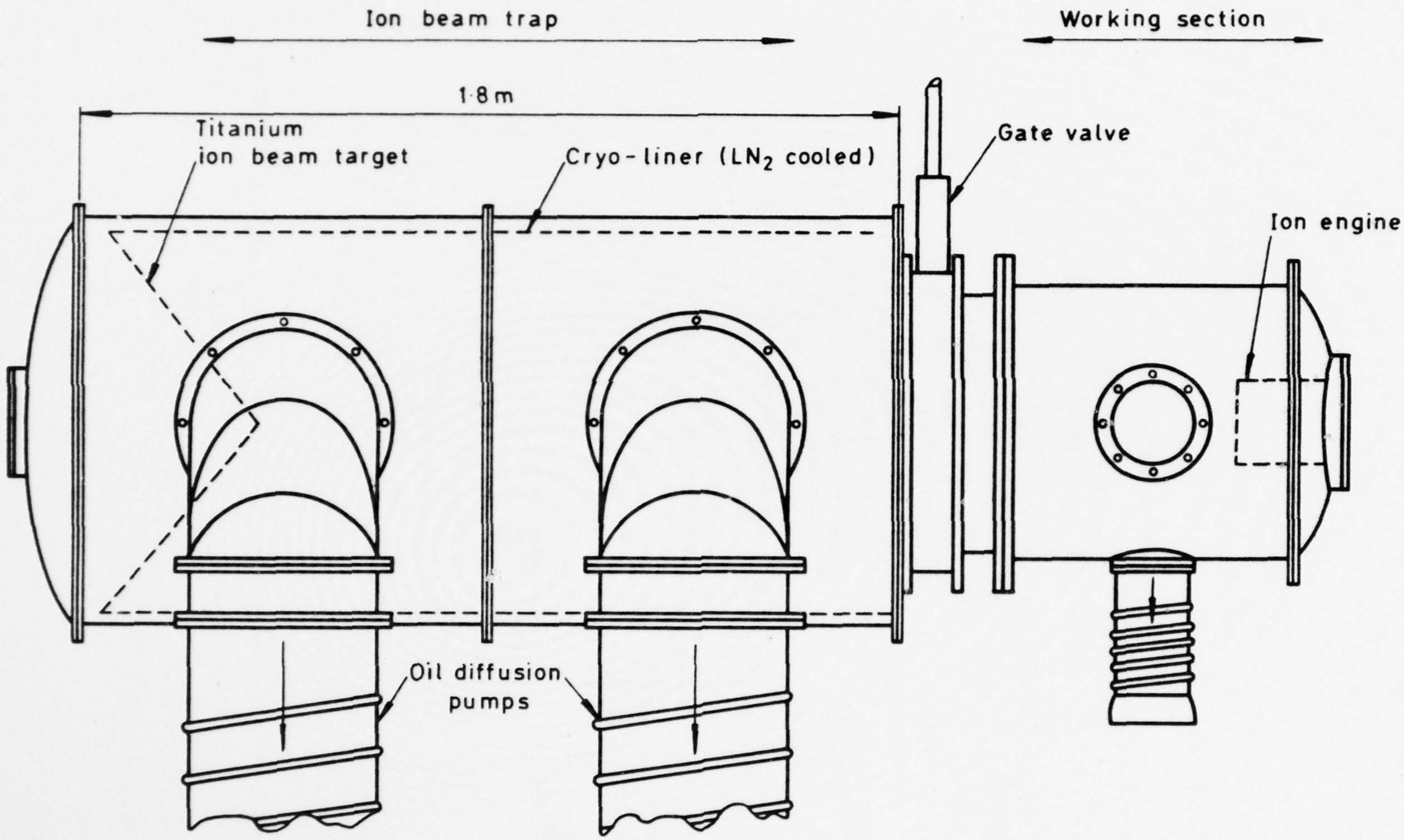

Fig.50 Schematic diagram of RAE 0·9m ion thruster test facility

Fig. 51

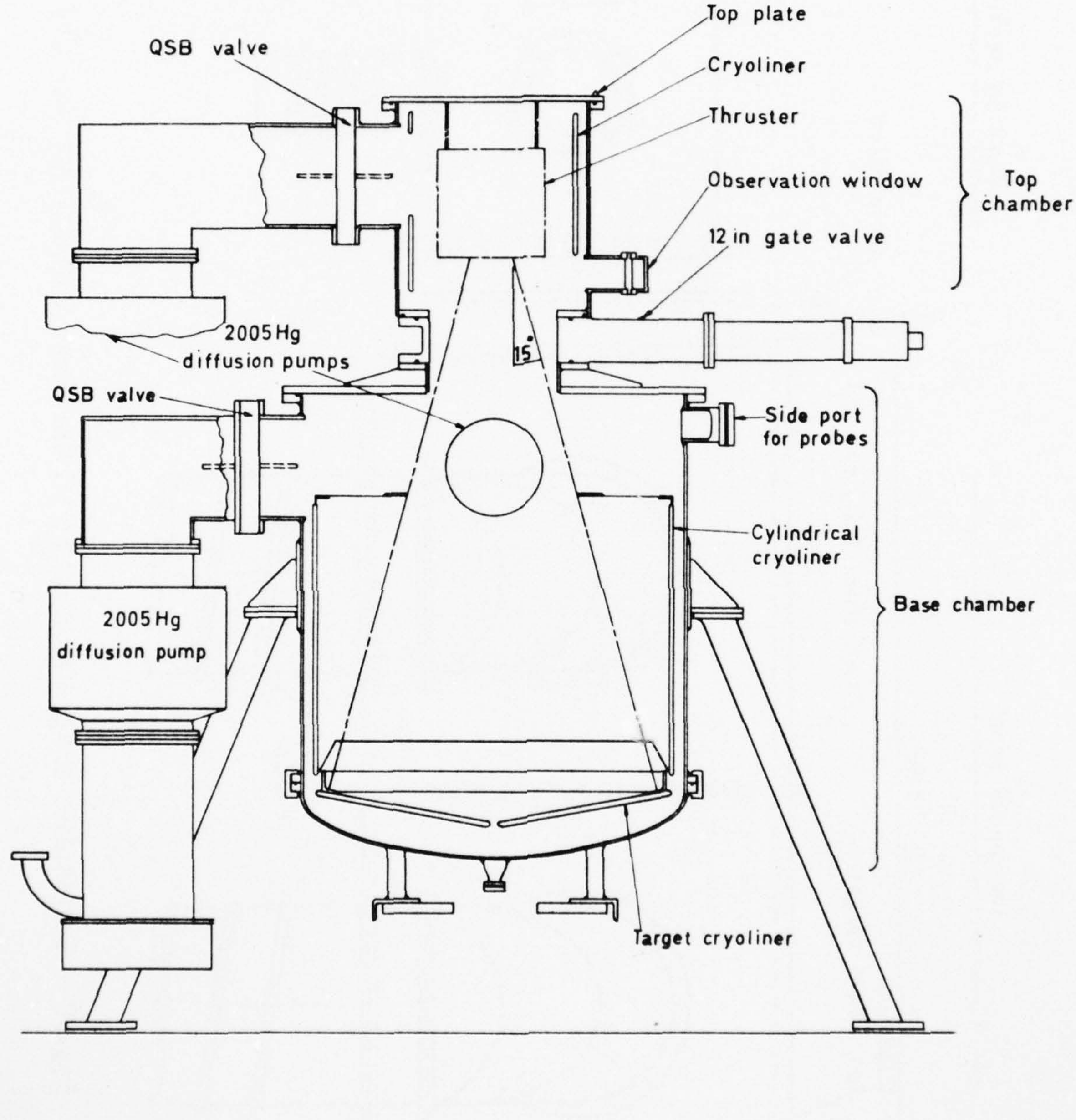

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Fig. 51 Schematic of test facility at the Fulmer Research Institute

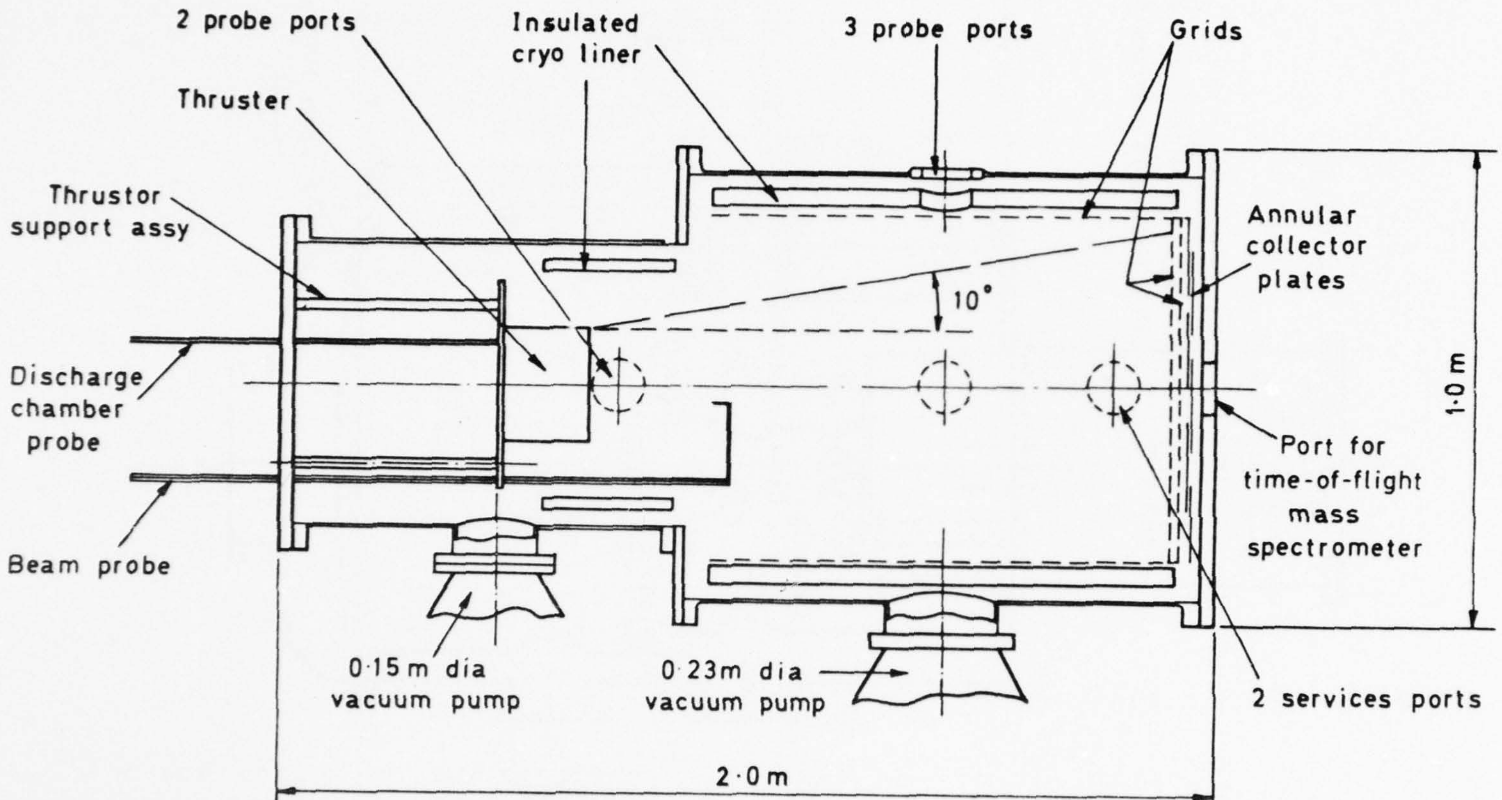

Fig.52 Culham 1m diameter horizontal test facility

Fig. 53

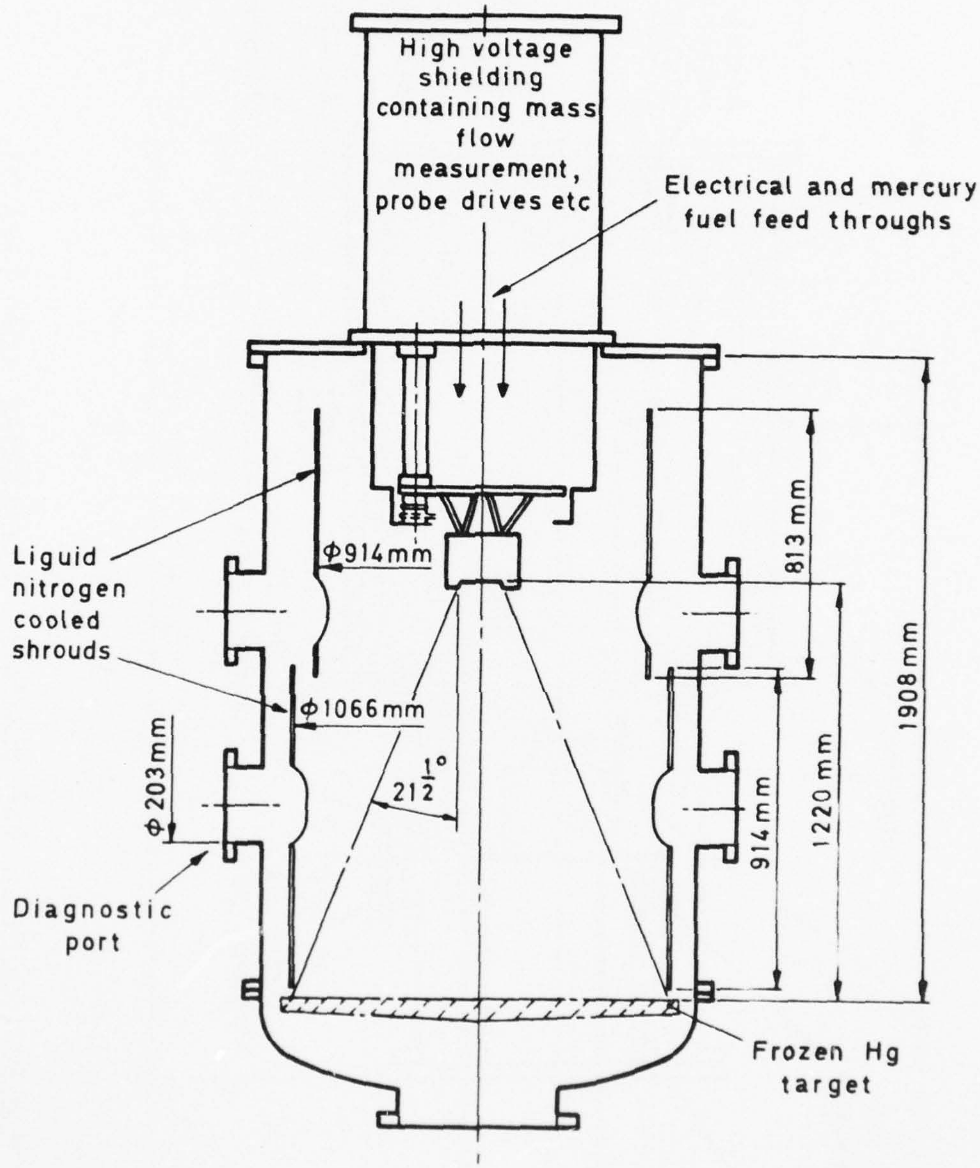

Fig. 53 Schematic diagram of the vertical test facility at Culham

Fig. 54

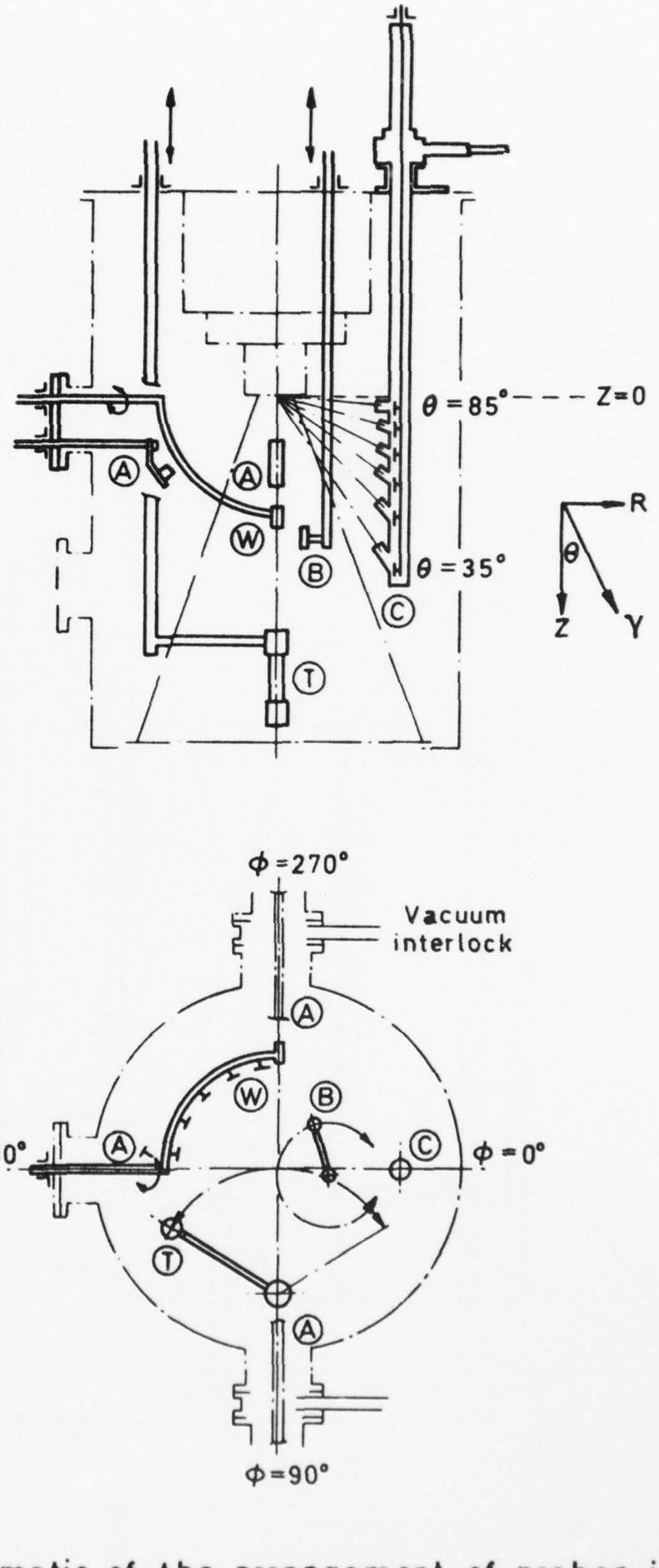

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Fig. 54 Schematic of the arrangement of probes in the Culham vertical test facility

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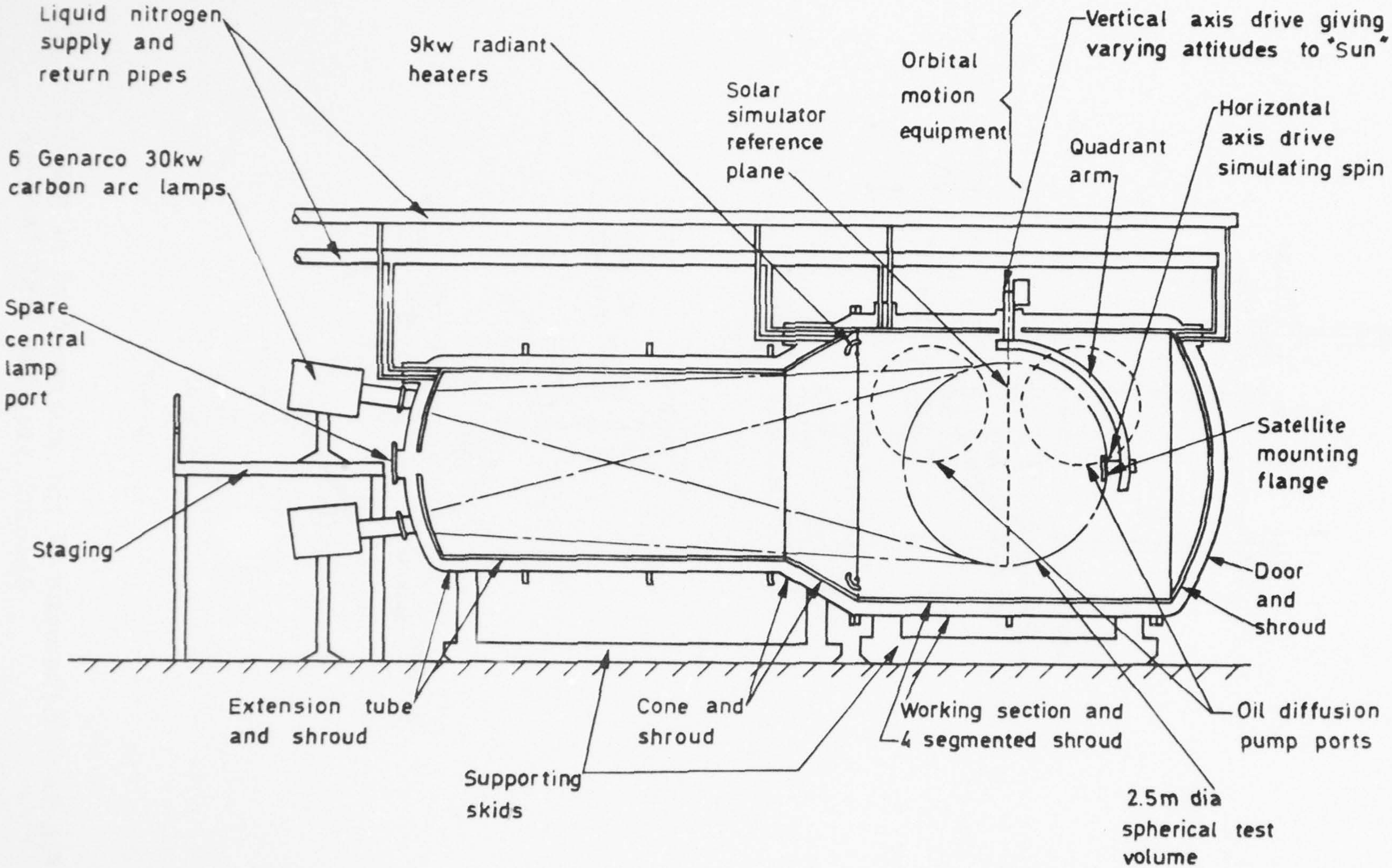
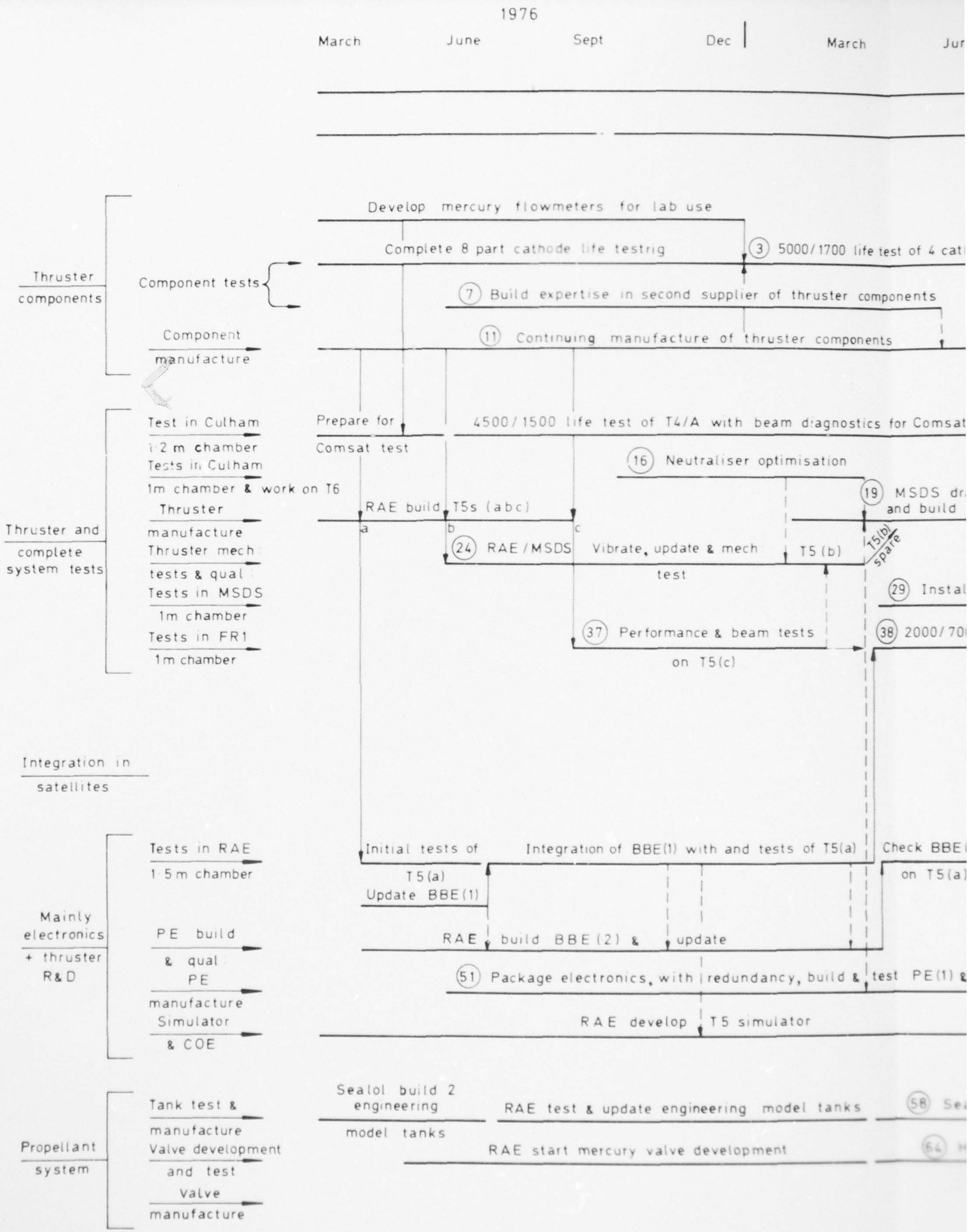


Fig. 55 Diagram of 2.5 m diameter space simulation facility at RAE


1976
March
June
Sept
Dec
March
Jur
Develop mercury flowmeters for lab use
Complete 8 part cathode life testrig
3 5000/1700 life test of 4 cat
Thruster components
Component tests
7 Build expertise in second supplier of thruster components
Component manufacture
11 Continuing manufacture of thruster components
Test in Culham 1·2 m chamber
Prepare for Comsat test
4500/1500 life test of T4/A with beam diagnostics for Comsat
Tests in Culham 1m chamber & work on T6
16 Neutraliser optimisation
Thruster manufacture
RAE build T5s (abc)
a
b
c
19 MSDS dr and build
Thruster and complete system tests
Thruster mech tests & qual
24 RAE/MSDS Vibrate, update & mech test
T5 (b)
T5(b) spare
Tests in MSDS 1m chamber
29 Instal
Tests in FR1 1m chamber
37 Performance & beam tests on T5(c)
38 2000/70
Integration in satellites
Tests in RAE 1·5 m chamber
Initial tests of T5(a) Update BBE(1)
Integration of BBE(1) with and tests of T5(a)
Check BBE on T5(a)
Mainly electronics + thruster R&D
PE build & qual
RAE build BBE(2) & update
PE manufacture
51 Package electronics, with redundancy, build & test PE(1) &
Simulator & COE
RAE develop T5 simulator
Tank test & manufacture
Sealol build 2 engineering model tanks
RAE test & update engineering model tanks
58 Se
Propellant system
Valve development and test
RAE start mercury valve development
64
Valve manufacture

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THE UK ION THRUSTER SYSTEM AND A PROPOSED FUTURE PROGRAMME.(U)
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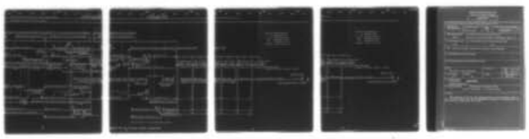

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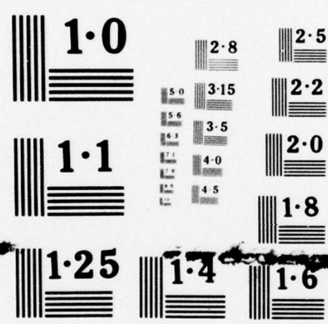
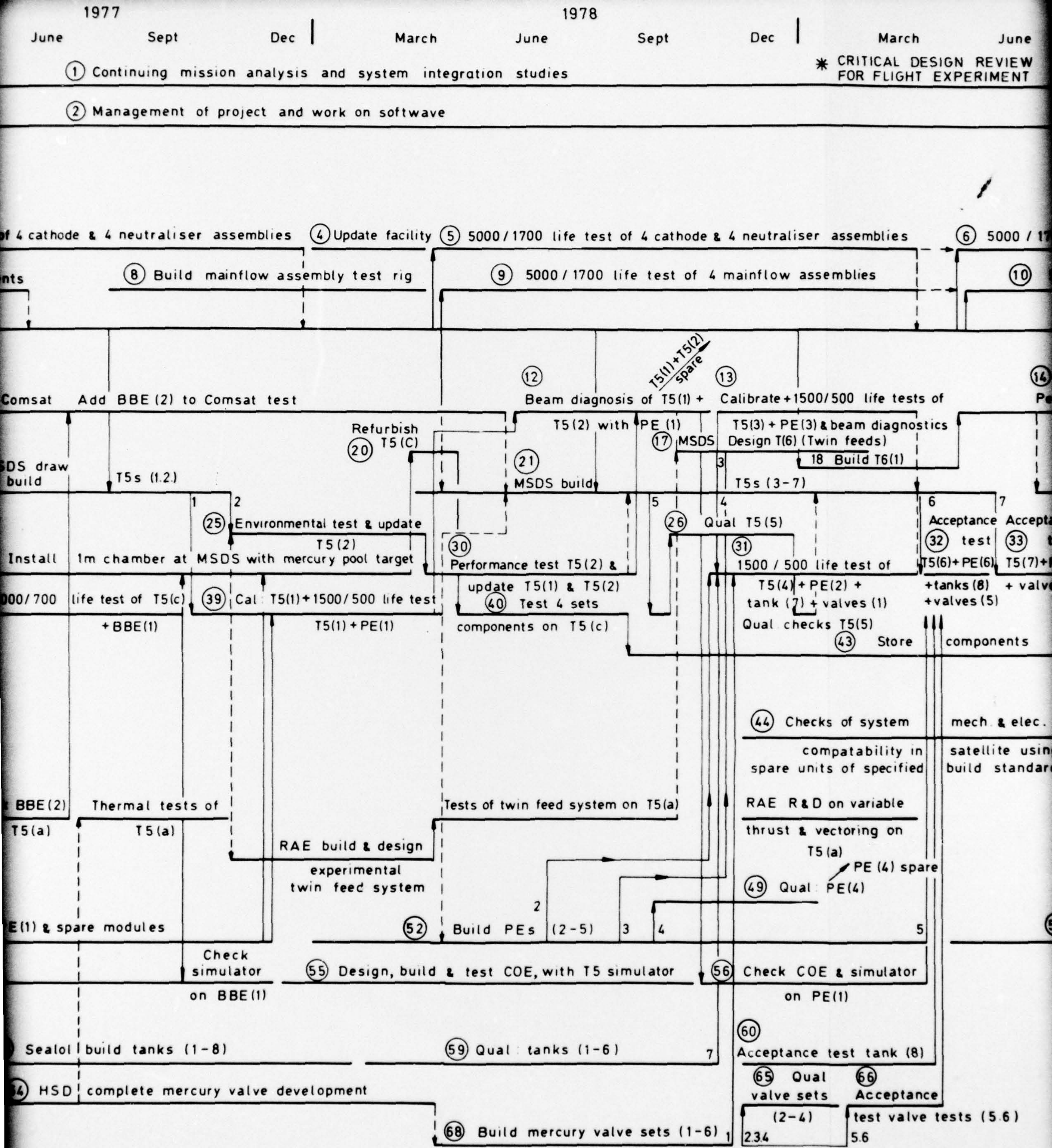
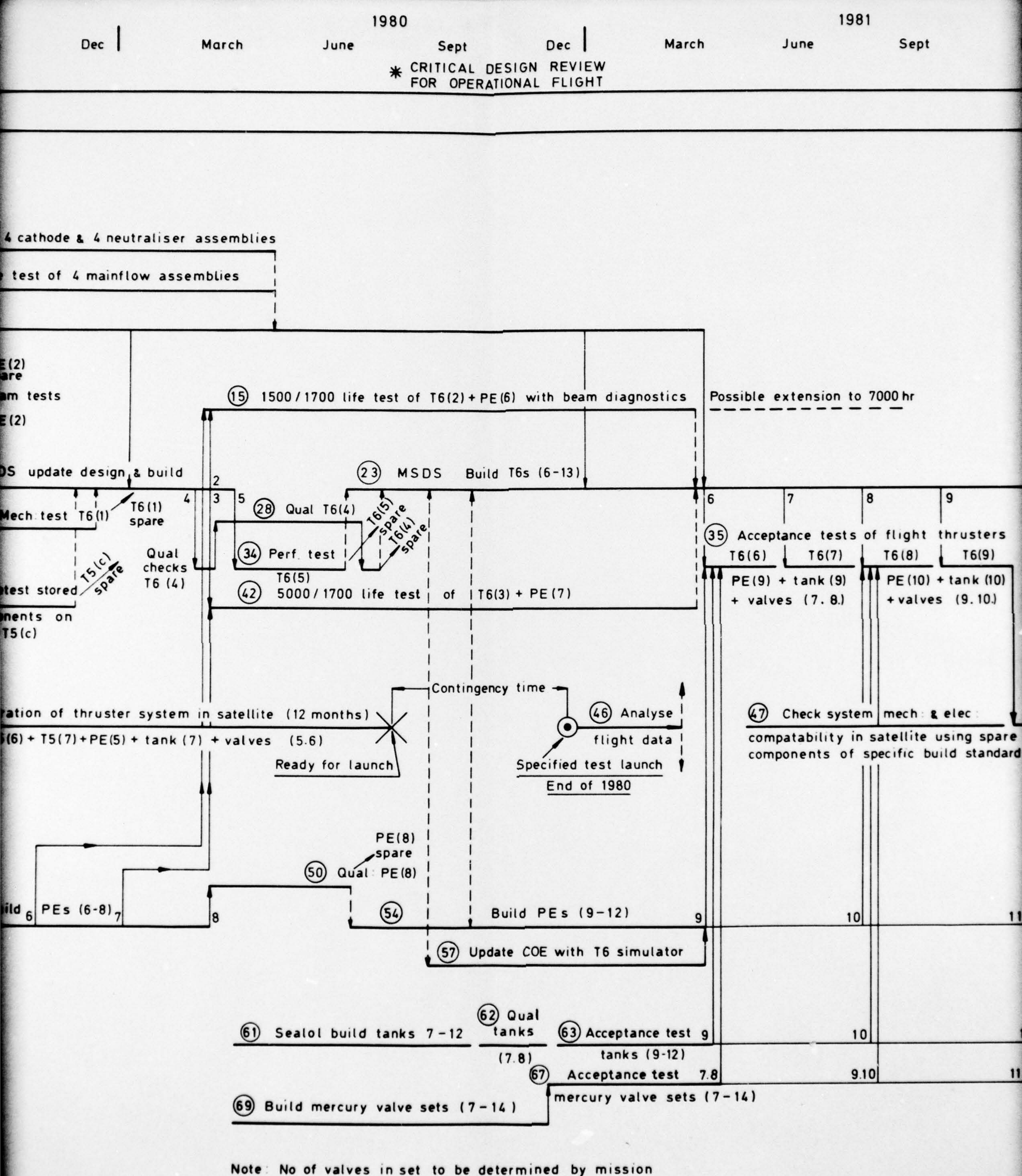


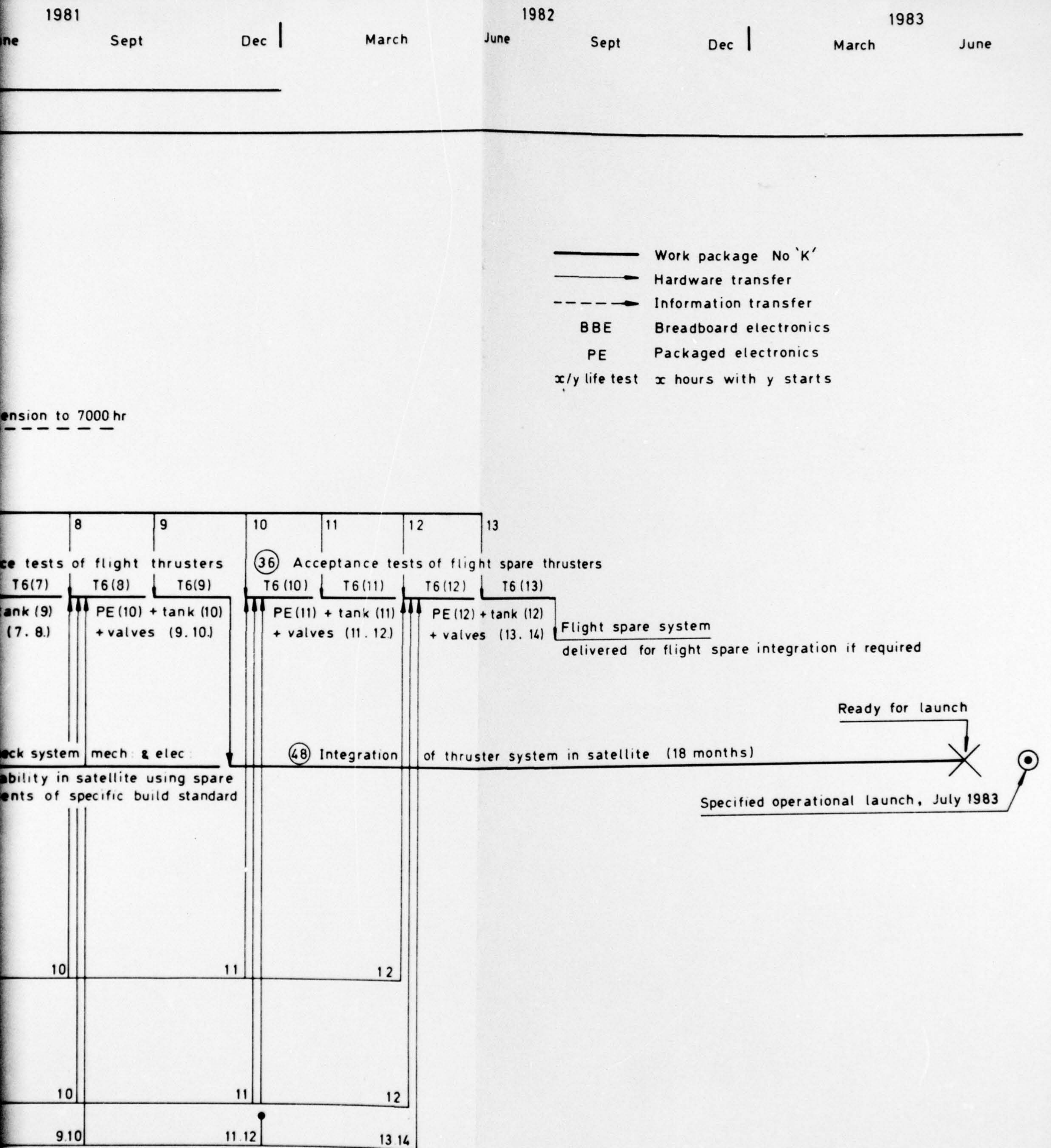
NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART


1977
1978
June
Sept
Dec
March
June
Sept
Dec
March
June
* CRITICAL DESIGN REVIEW FOR FLIGHT EXPERIMENT
1 Continuing mission analysis and system integration studies
2 Management of project and work on softwave
of 4 cathode & 4 neutraliser assemblies
4 Update facility
5 5000 / 1700 life test of 4 cathode & 4 neutraliser assemblies
6 5000 / 17
nts
8 Build mainflow assembly test rig
9 5000 / 1700 life test of 4 mainflow assemblies
10
Comsat
Add BBE (2) to Comsat test
12 Beam diagnosis of T5(1) + T5(2) with PE (1)
T5(1)+T5(2) spare
13 Calibrate + 1500/500 life tests of T5(3) + PE(3) & beam diagnostics
14
Pe
Refurbish T5(C)
20
17 MSDS Design T(6) (Twin feeds)
18 Build T6(1)
SDS draw build
T5s (1.2.)
21 MSDS build
T5s (3-7)
1
2
3
4
5
6
7
25 Environmental test & update T5(2)
26 Qual T5(5)
Acceptance
Accepta
32 test
33
Install 1m chamber at MSDS with mercury pool target
30 Performance test T5(2) & update T5(1) & T5(2)
31 1500 / 500 life test of T5(4) + PE(2) + tank (7) + valves (1)
T5(6)+PE(6) +tanks (8) +valves (5)
T5(7)+P + valve
000/700 life test of T5(c) + BBE(1)
39 Cal T5(1) + 1500/500 life test T5(1) + PE(1)
40 Test 4 sets components on T5(c)
Qual checks T5(5)
43 Store components
44 Checks of system compatability in spare units of specified
mech & elec. satellite using build standard
BBE(2) T5(a)
Thermal tests of T5(a)
Tests of twin feed system on T5(a)
RAE R&D on variable thrust & vectoring on T5 (a)
RAE build & design experimental twin feed system
PE (4) spare
49 Qual PE(4)
E(1) & spare modules
52 Build PEs (2-5)
2
3
4
5
Check simulator on BBE(1)
55 Design, build & test COE, with T5 simulator
56 Check COE & simulator on PE(1)
60 Acceptance test tank (8)
Sealol build tanks (1-8)
59 Qual tanks (1-6)
7
65 Qual valve sets (2-4)
66 Acceptance test valve tests (5.6)
64 HSD complete mercury valve development
68 Build mercury valve sets (1-6)
1
2.3.4
5.6

2

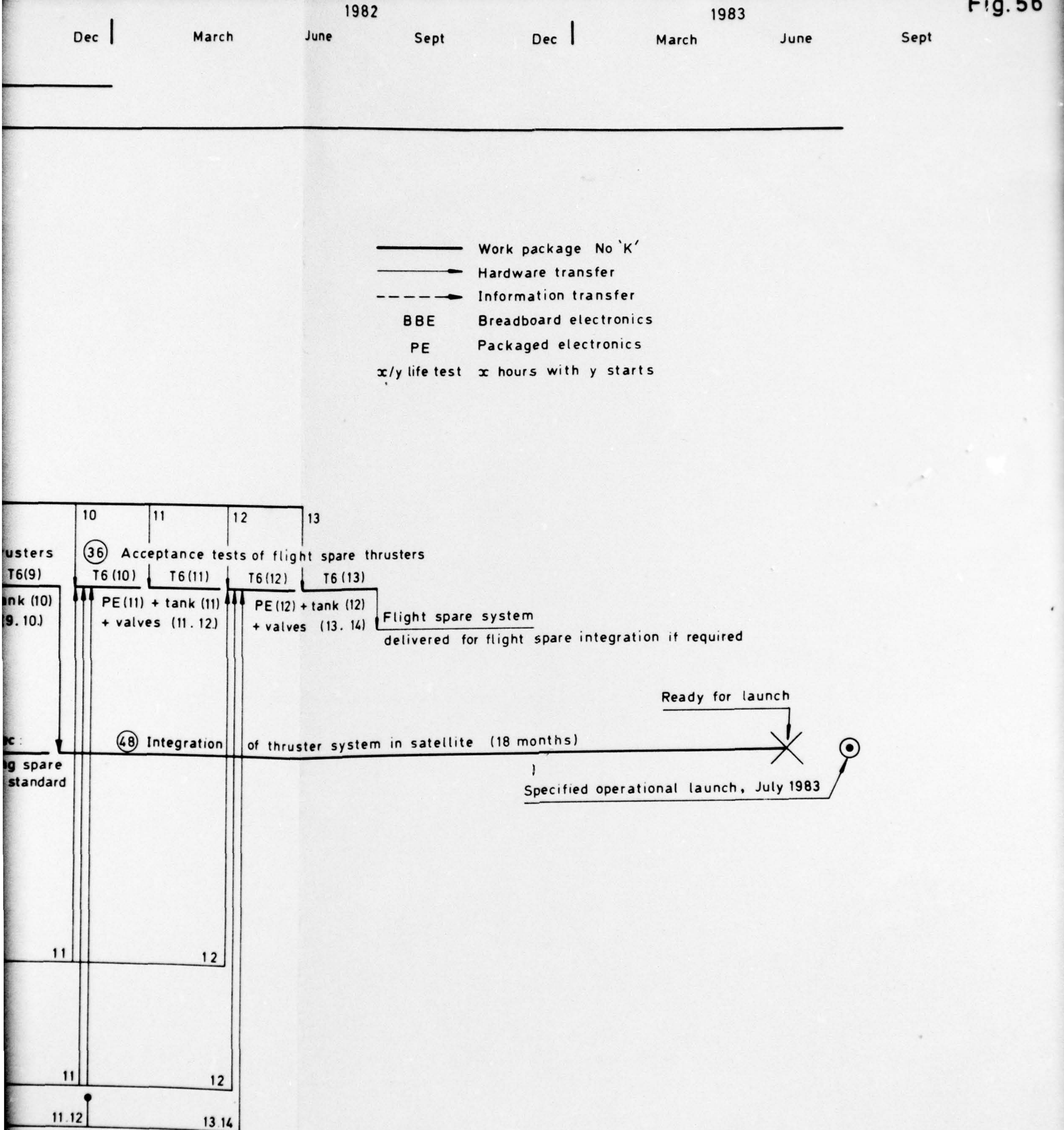


roposed UK ion thruster system programme 3



1981
1982
1983
ne
Sept
Dec
March
June
Sept
Dec
March
June
Work package No 'K'
Hardware transfer
Information transfer
BBE Breadboard electronics
PE Packaged electronics
x/y life test x hours with y starts
ension to 7000 hr
8
9
10
11
12
13
ce tests of flight thrusters
36 Acceptance tests of flight spare thrusters
T6(7)
T6(8)
T6(9)
T6(10)
T6(11)
T6(12)
T6(13)
ank (9)
(7. 8.)
PE(10) + tank (10)
+ valves (9. 10.)
PE(11) + tank (11)
+ valves (11. 12.)
PE(12) + tank (12)
+ valves (13. 14)
Flight spare system
delivered for flight spare integration if required
Ready for launch
ck system mech & elec
48 Integration of thruster system in satellite (18 months)
ability in satellite using spare
ents of specific build standard
Specified operational launch, July 1983
10
11
12
10
11
12
9.10
11.12
13.14

Fig. 56



1982
1983
Dec
March
June
Sept
Dec
March
June
Sept
Work package No 'K'
Hardware transfer
Information transfer
BBE Breadboard electronics
PE Packaged electronics
x/y life test x hours with y starts
10
11
12
13
usters
36 Acceptance tests of flight spare thrusters
T6(9)
T6 (10)
T6 (11)
T6 (12)
T6 (13)
nk (10)
9. 10.)
PE (11) + tank (11)
+ valves (11. 12.)
PE (12) + tank (12)
+ valves (13. 14)
Flight spare system
delivered for flight spare integration if required
Ready for launch
c:
48 Integration of thruster system in satellite (18 months)
g spare
standard
Specified operational launch, July 1983
11
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11.12
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4

5

REPORT DOCUMENTATION PAGE

Overall security classification of this page

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7b. (For Conference Papers) Title, Place and Date of Conference

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Electric propulsion. Ion thruster system.

17. Abstract

The technology of the UK's ion thruster system and its development status in May 1976 are described and a detailed programme is proposed for developing the complete system for operational use in 1983.

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